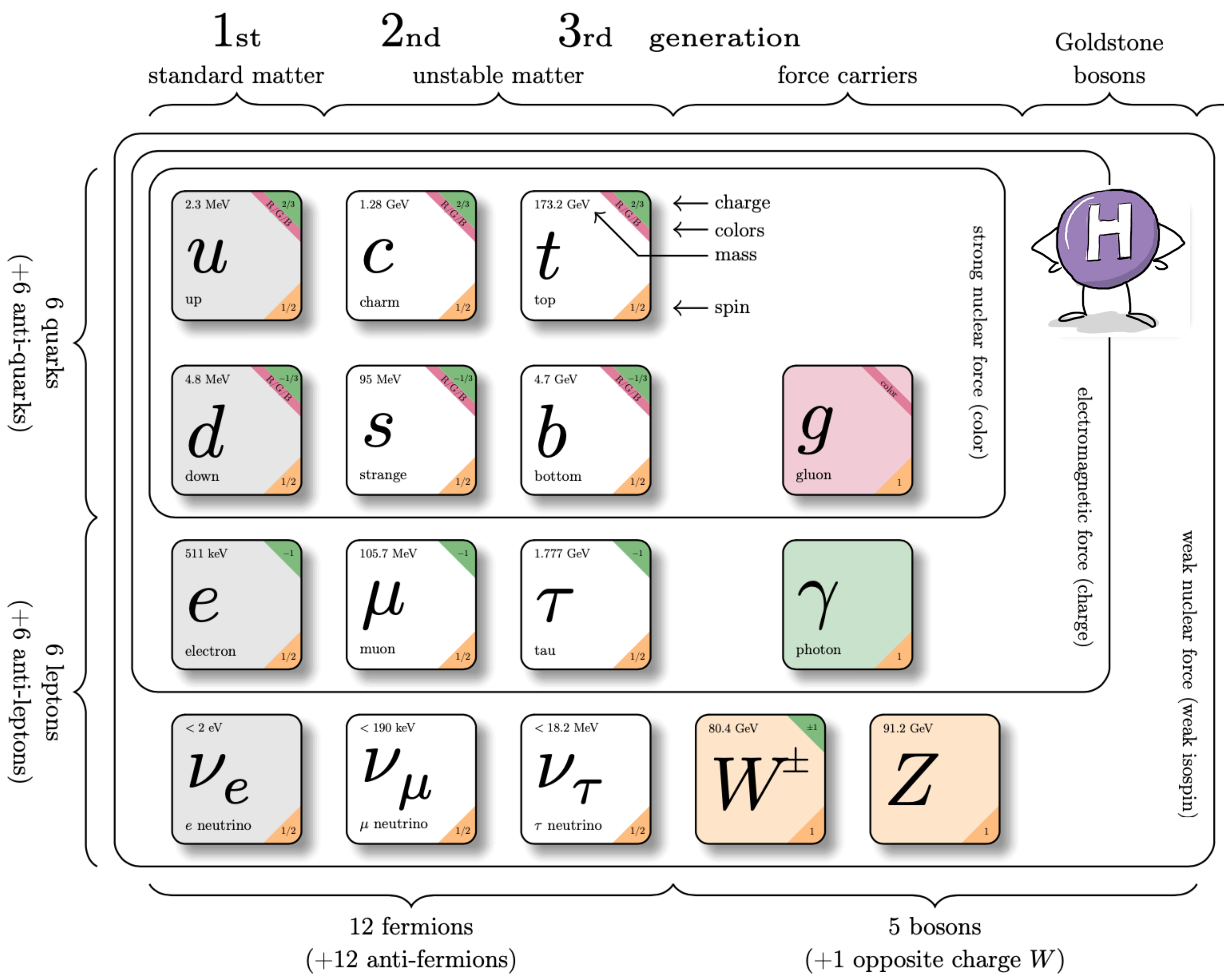
Higgs Hunting
21/09/2021

CMS Higgs Combination

Matteo Bonanomi
(LLR, Ecole Polytechnique, CNRS)
On behalf of the CMS Collaboration

The Higgs sector

The **Higgs boson** is a **scalar particle**, regulates the **EWSB mechanism**, and it couples with:



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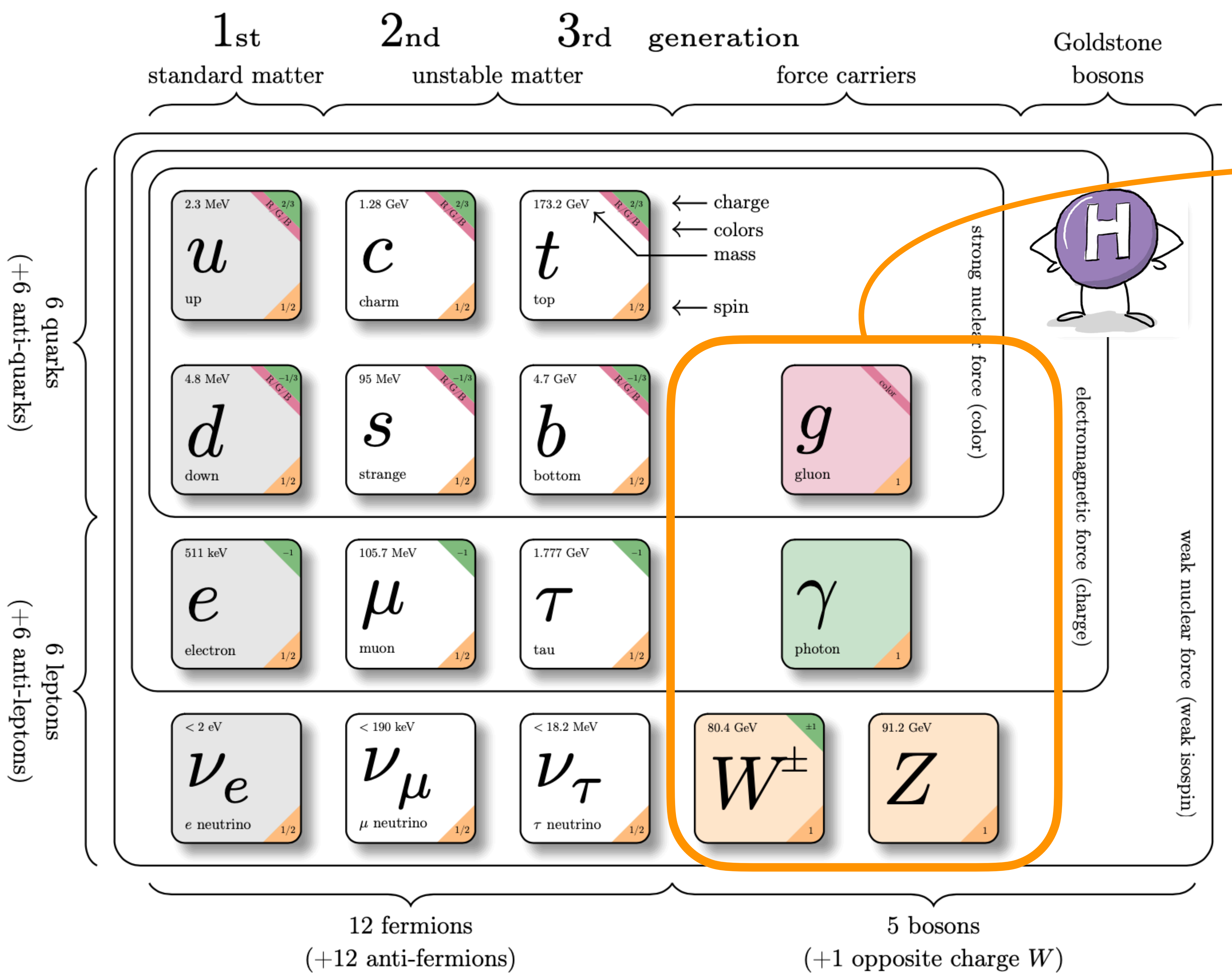
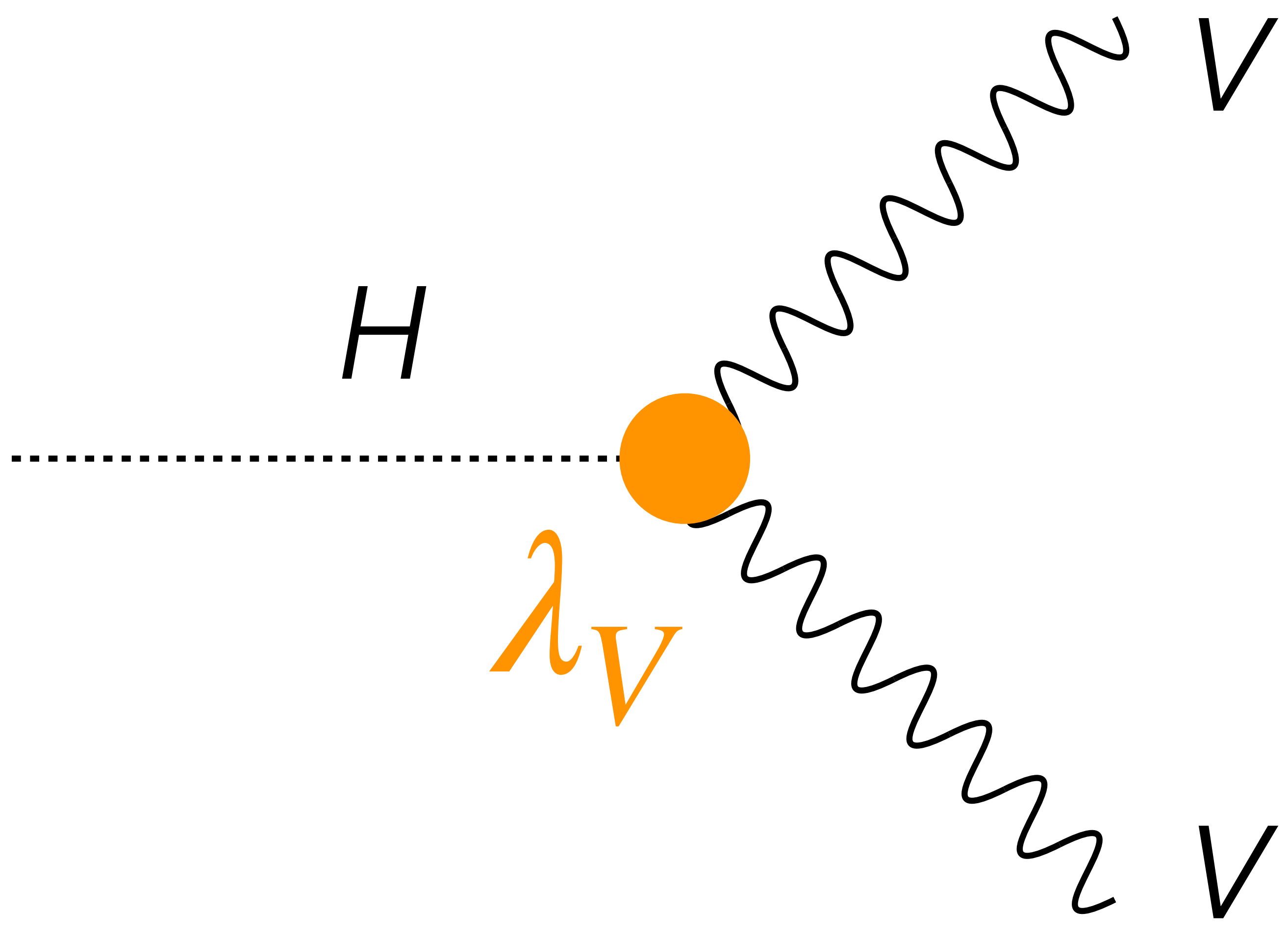


Couplings to gauge bosons: $\lambda_V = \frac{2}{v} m_V^2$



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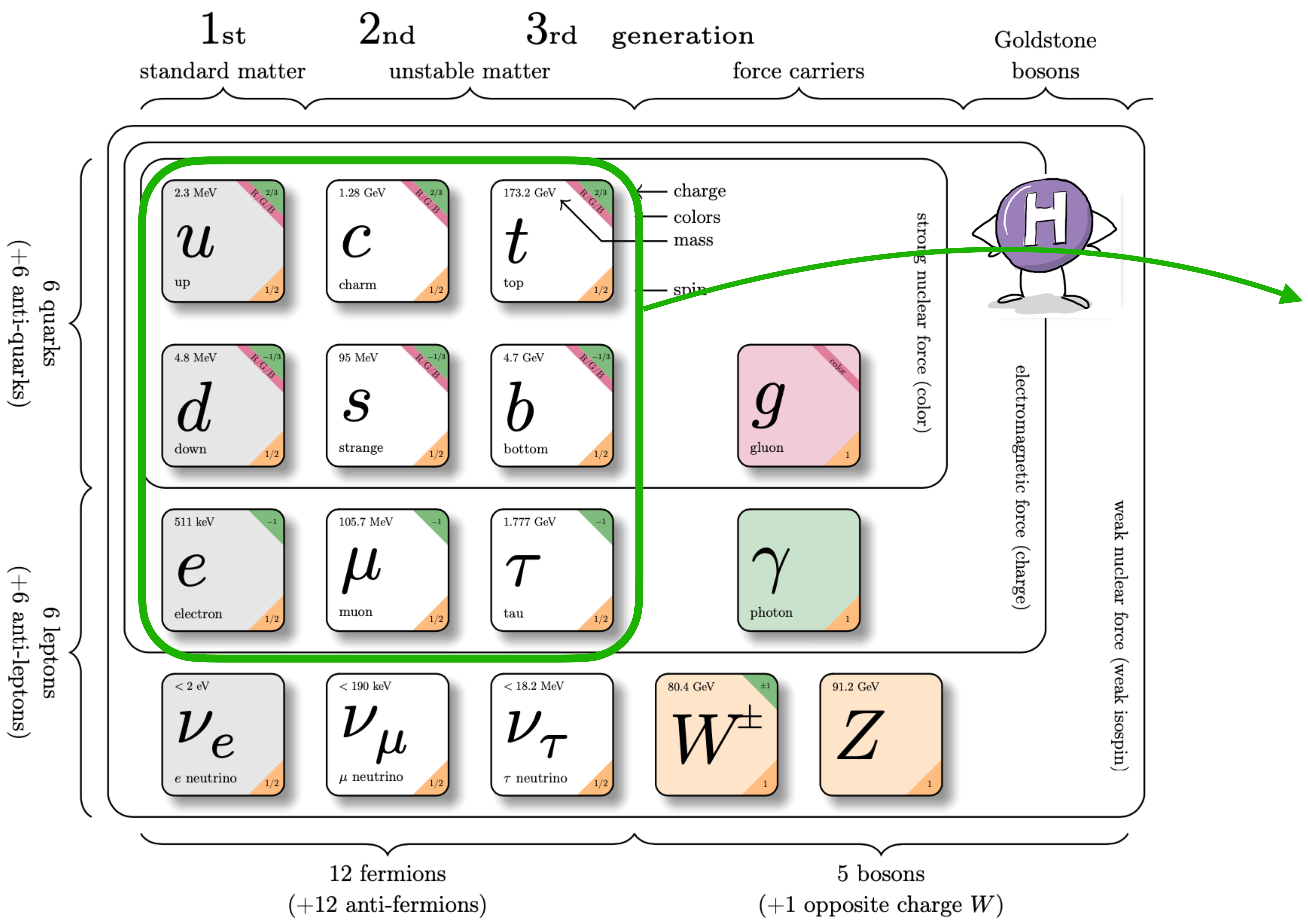

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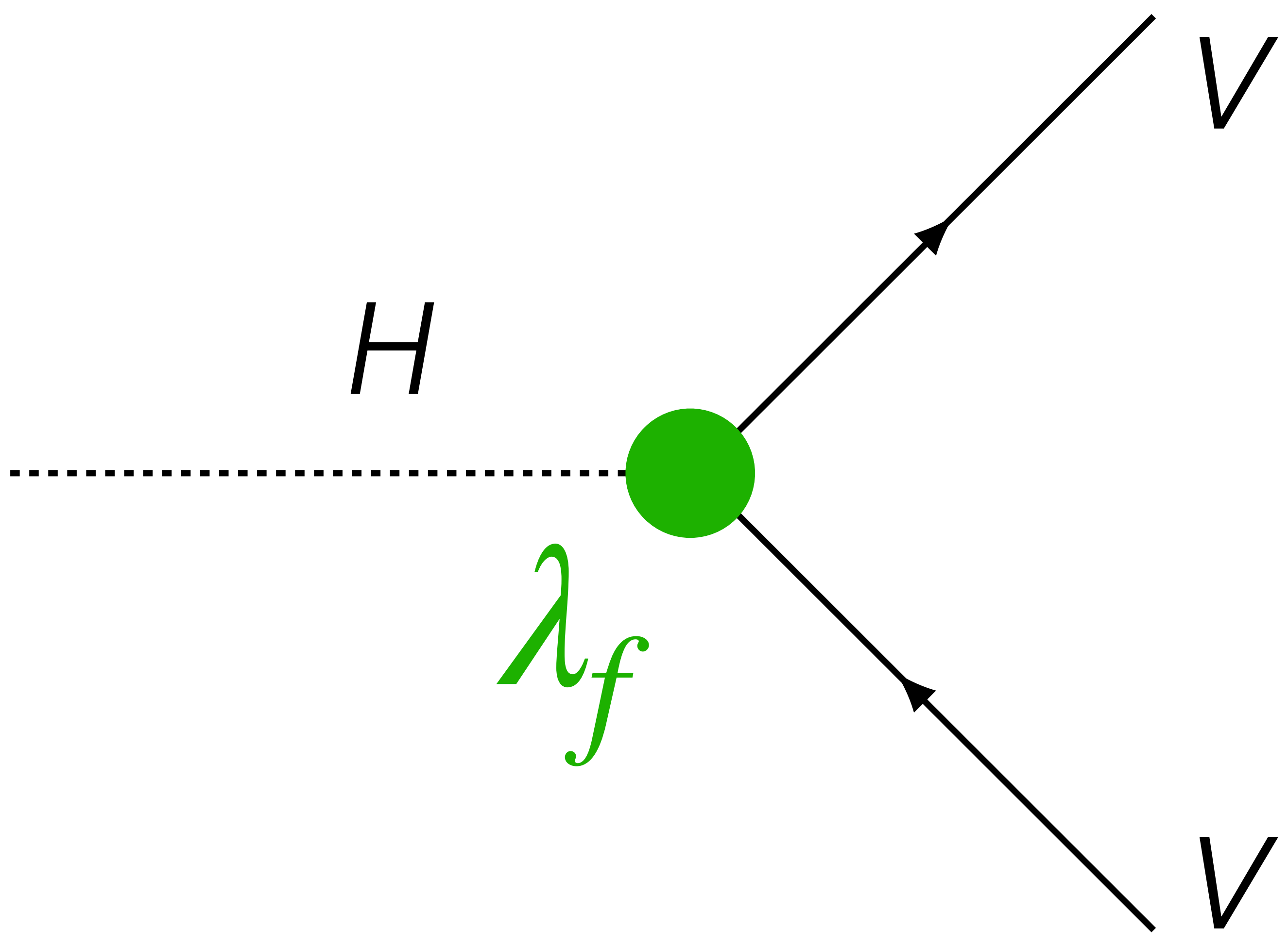
Couplings to fermions: $\lambda_f = \frac{\sqrt{2}}{v} m_f$



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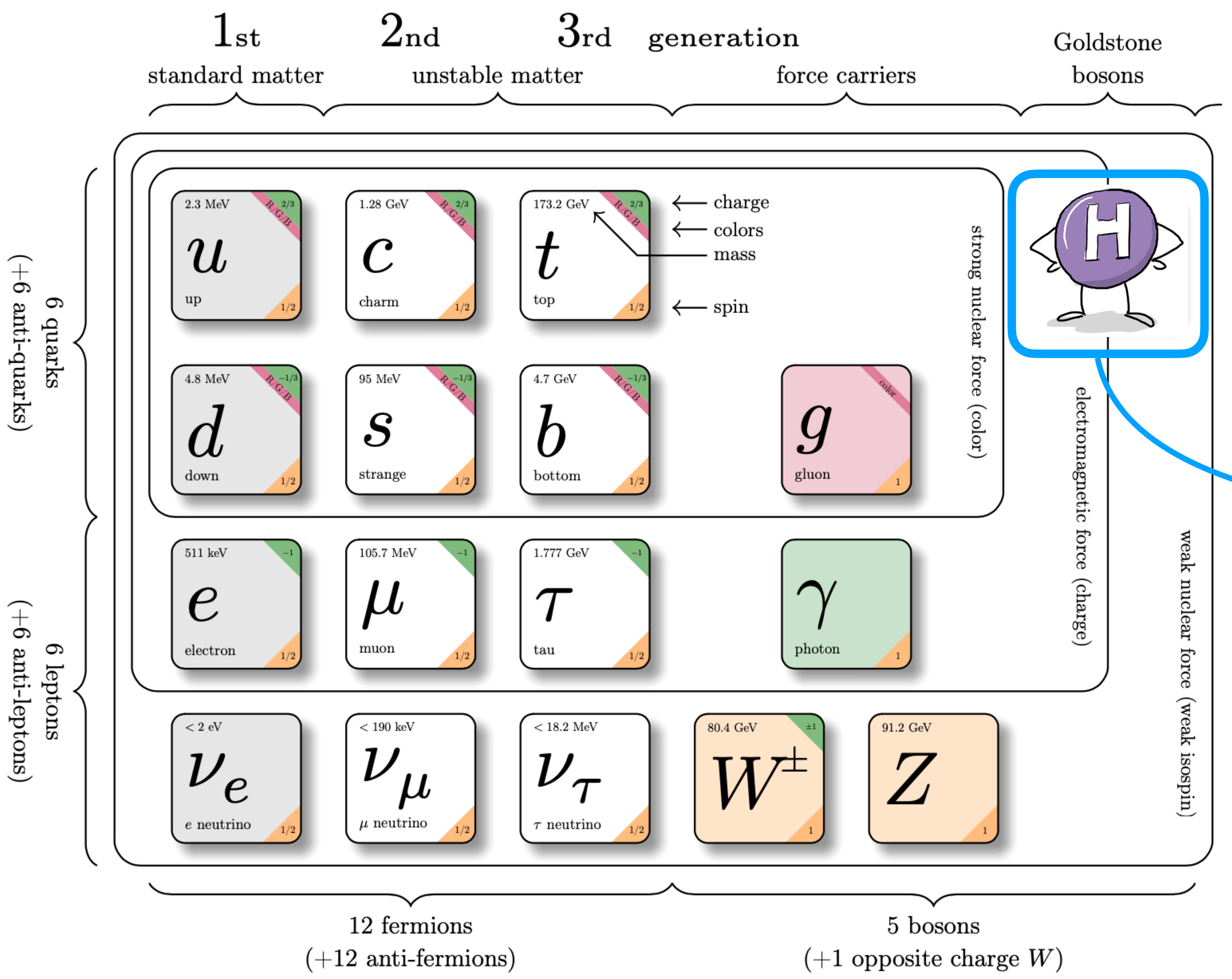

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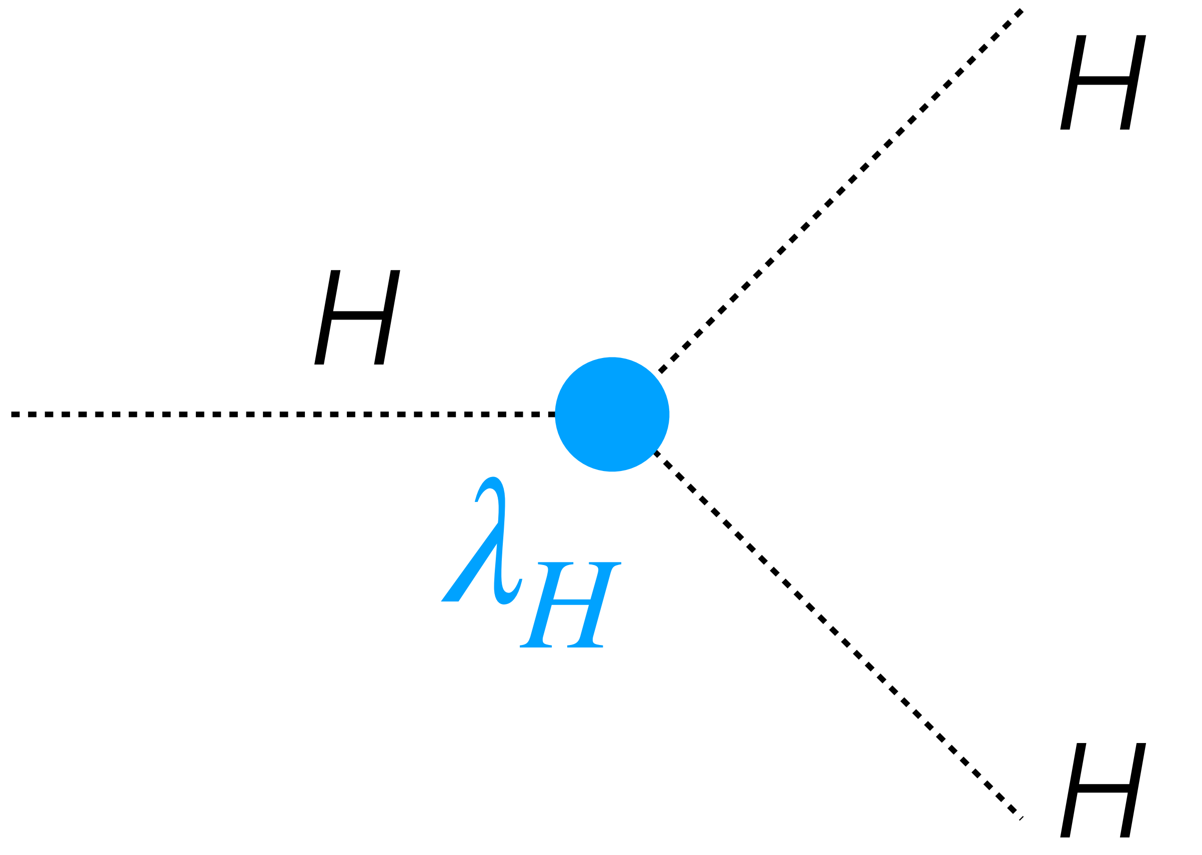
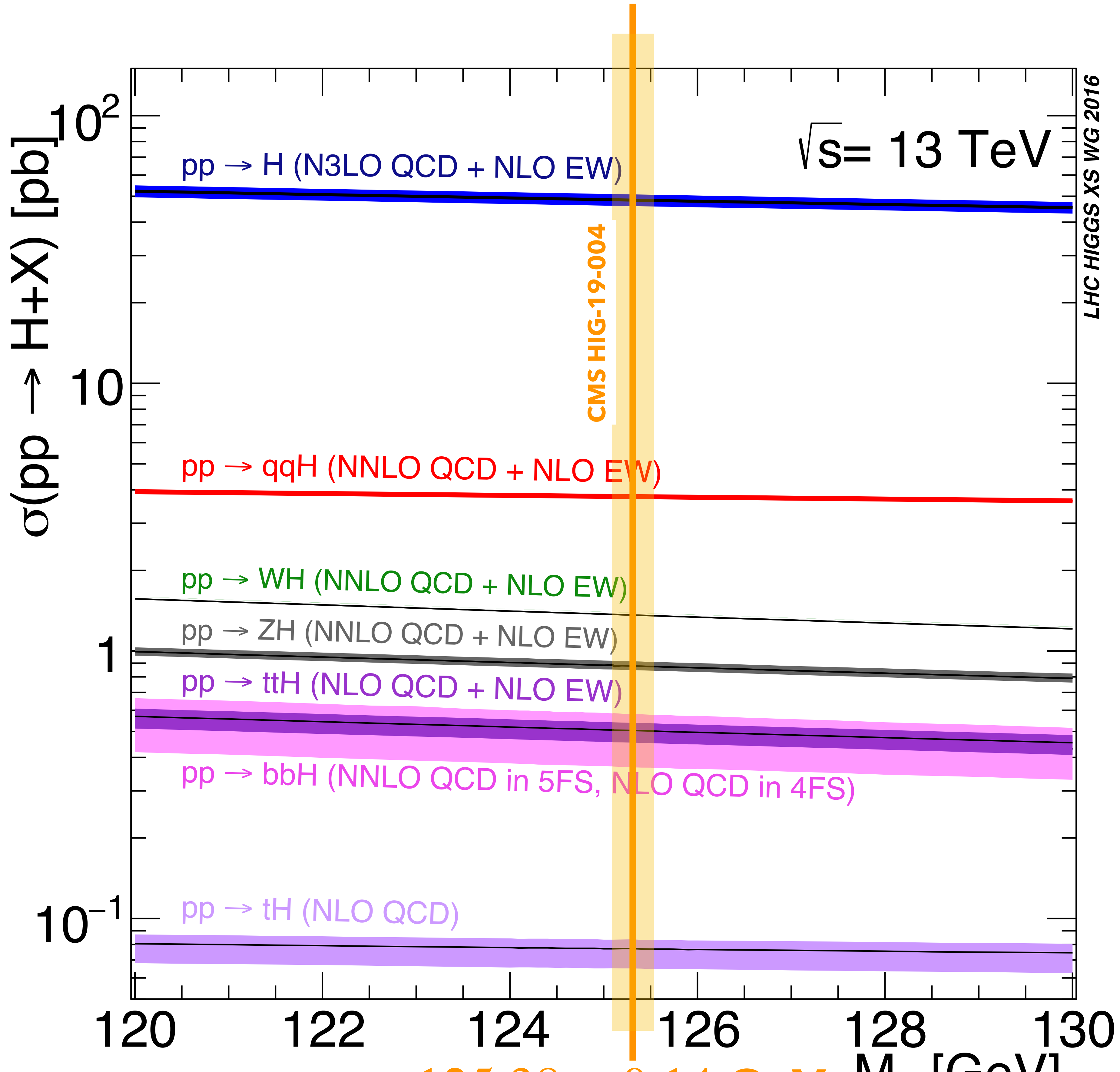
Higgs boson self-coupling: $\lambda_H = \frac{m_H^2}{v^2}$



The Higgs sector at the LHC

In 2015 LHC started the **Run II** phase, opening the doors for the ***precision physics era***, with the goal of **precision measurements** of the **Higgs** boson **couplings**



$m_H = 125.38 \pm 0.14$ **GeV**

The large statistics and combination of different decay channels provide comprehensive assessment of H boson properties:

Production and decay rates

Higgs boson self coupling

EFT interpretations in STXS

Results from partial Run-II CMS Combination shown

The input analyses

References in Backup

Decay channel	Luminosity (fb^{-1})	ggH	VBF	VH	ttH
$H \to \gamma\gamma$	77	✓	✓		✓
$H \to ZZ^* \to 4\ell$	137	✓	✓	✓	✓
$H \to WW$	36	✓	✓	✓	
$H \to bb$	36 (ggH) - 77 (others)	✓		✓	✓
$H \to \tau\tau$	77	✓	✓	✓	
ttH multilepton	77				✓
$H \to \mu\mu$	36	✓	✓		

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$H \rightarrow \tau\tau$	77	✓	✓	✓	
ttH multilepton	77				✓
$H \rightarrow \mu\mu$	36	✓	✓		

Partial Run-II dataset(s), yet **comprehensive study** of the **H boson properties**.

Currently **working** on **full Run-II combination**

Signal strength modifiers

Scaling of production (i) or decay (f) of the SM Higgs boson as:

$$\mu_i = \frac{\sigma_i}{\left(\sigma_i\right)_{\mathrm{SM}}} \qquad \mu^f = \frac{B^f}{\left(B^f\right)_{\mathrm{SM}}}$$

The combined signal strength modifier is measured to be

$$\mu = 1.02 \pm 0.04(\mathrm{th}) \ \pm 0.04(\mathrm{exp}) \ \pm 0.04(\mathrm{stat})$$

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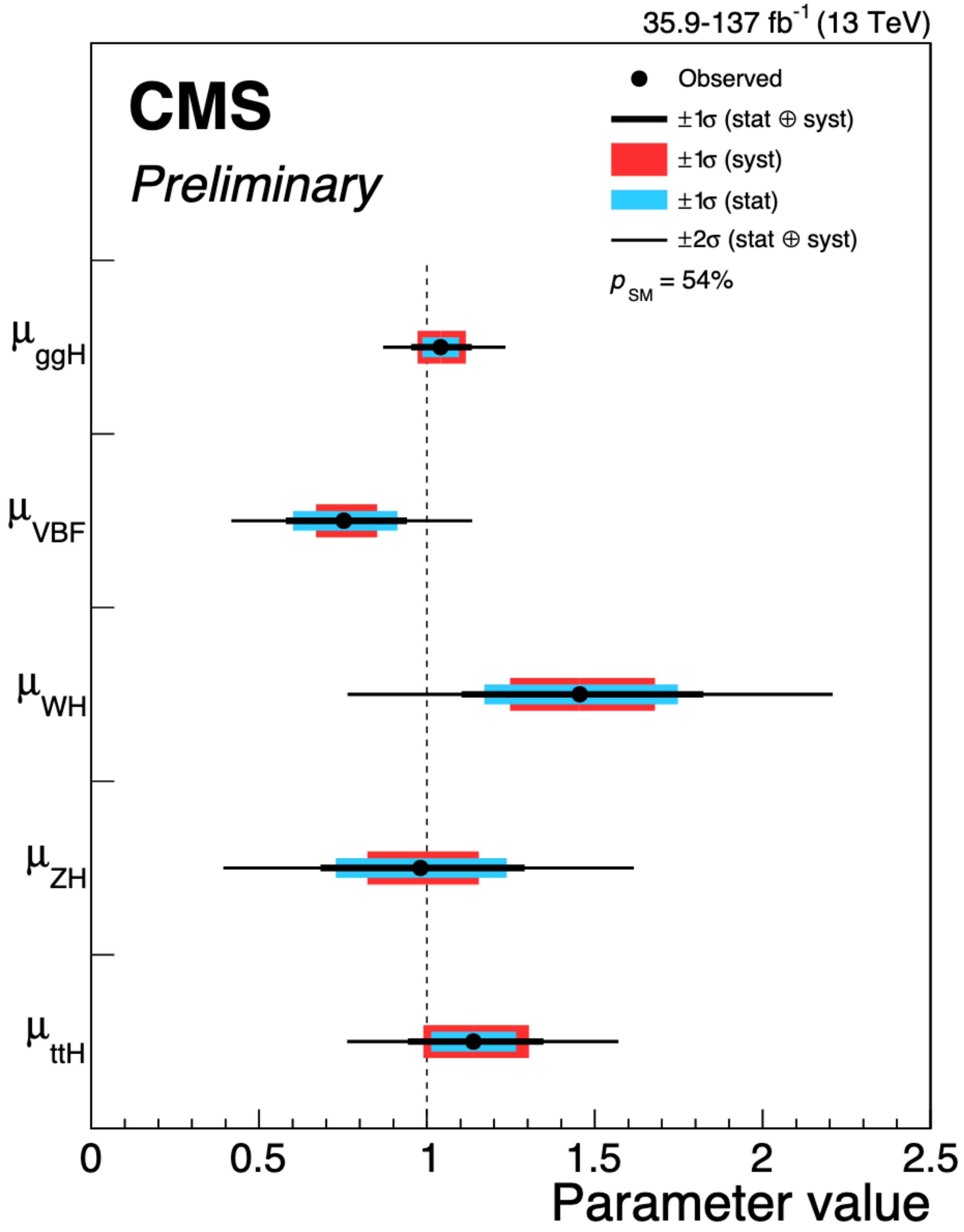
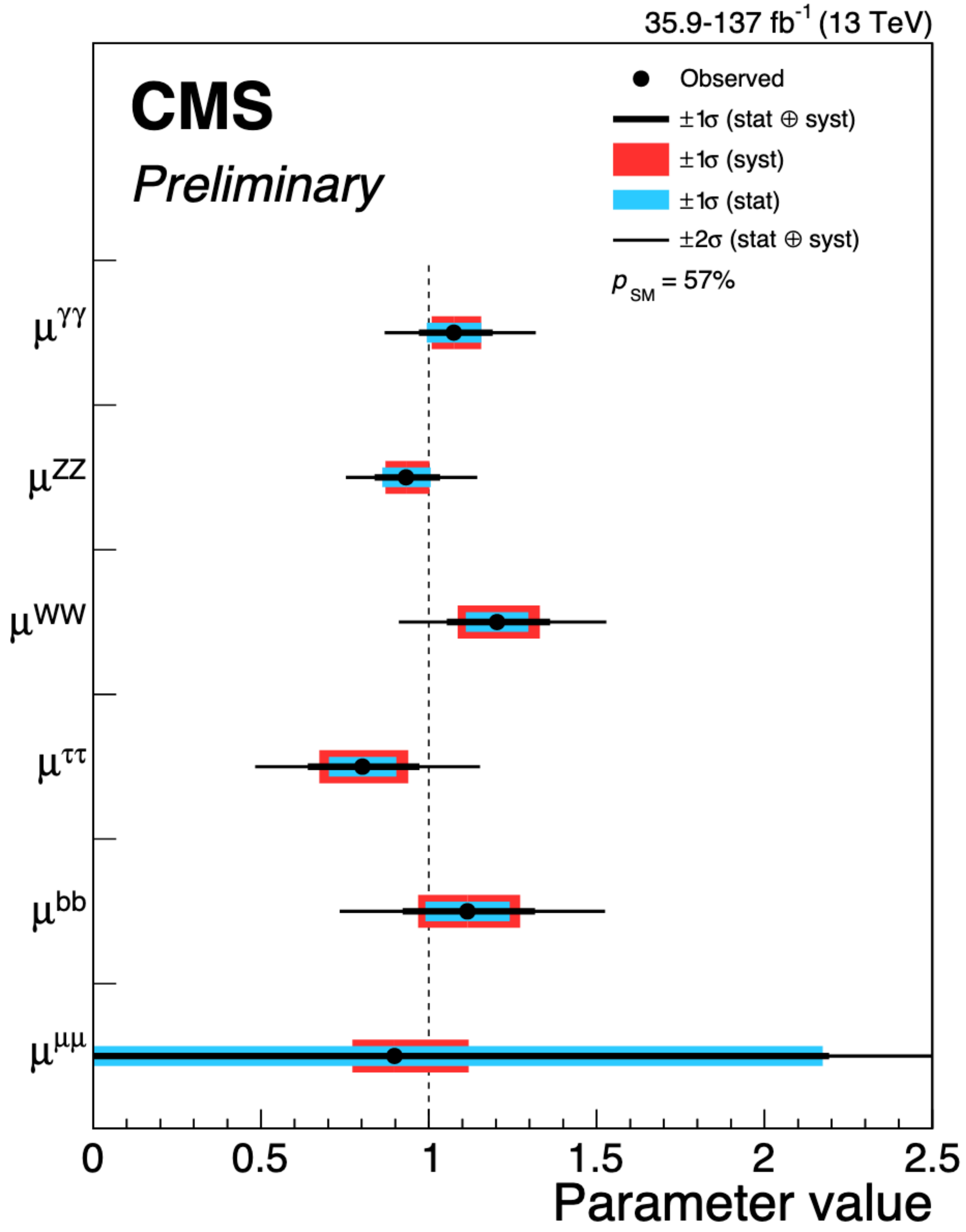
With the increasing statistics available from Run-II, the systematic uncertainties are becoming the **limiting factor for the ultimate precision** of the measurements, while statistical uncertainties are substantially **reduced in many decay channels**

Signal strength modifiers

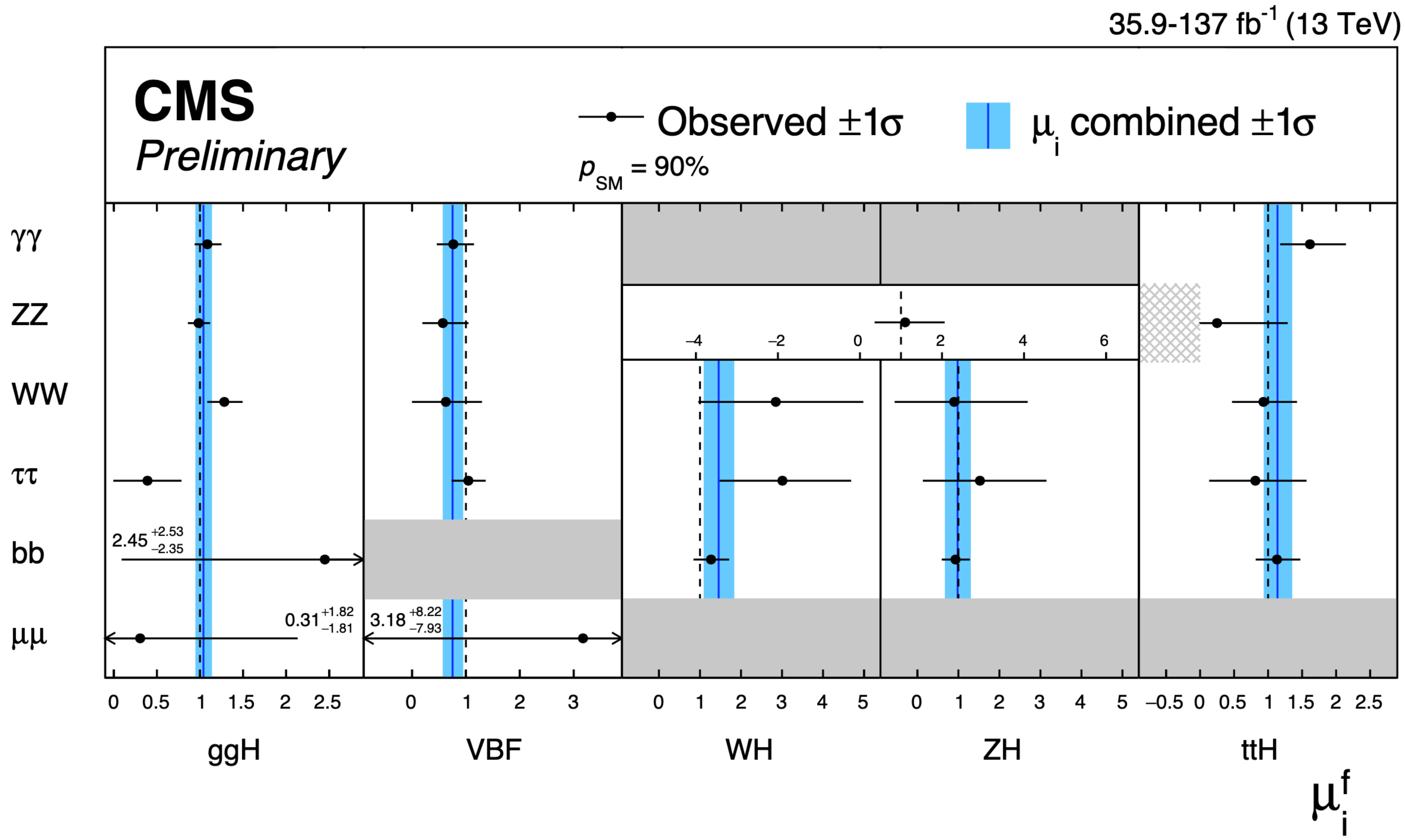
Simultaneous measurement of all the **production** and **decay signal strengths**





Signal strength modifiers

Measurement of **production times decay** μ_i^f from combination across decay channels



Signal strength modifiers

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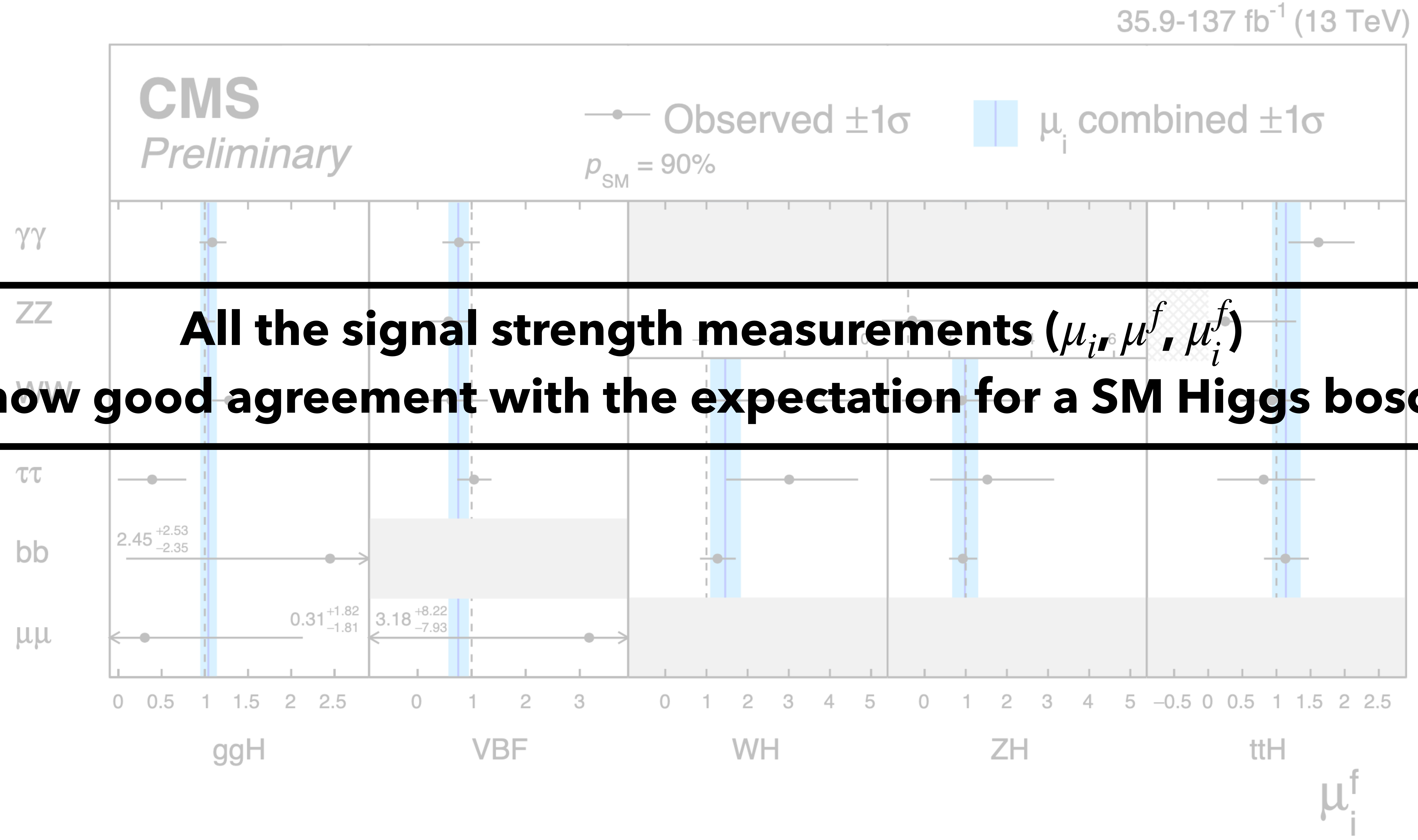
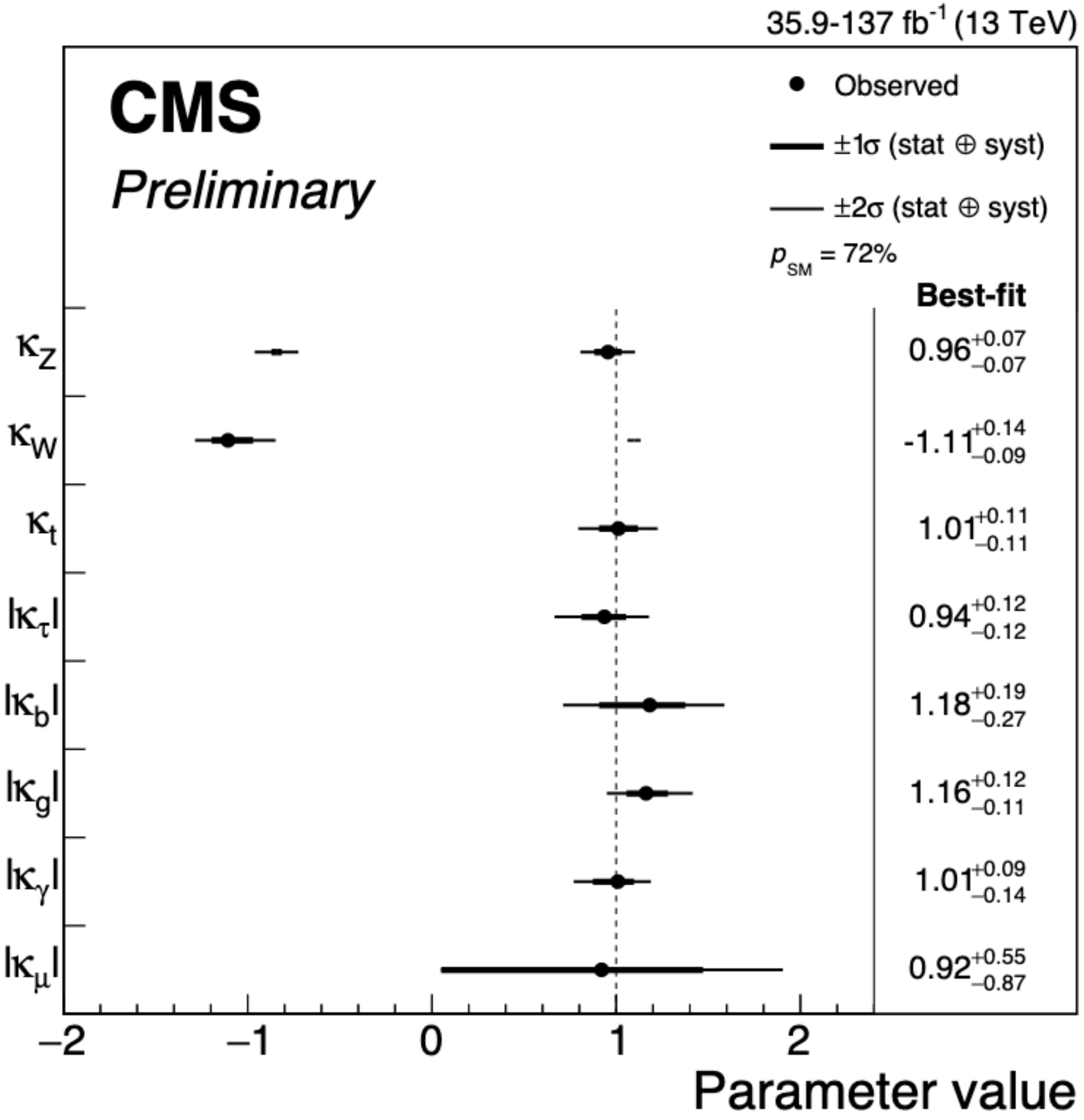


All the signal strength measurements (μ_i, μ^f, μ_i^f) show good agreement with the expectation for a SM Higgs boson

H boson couplings: κ-framework



Assuming only SM Higgs boson decays:

$$\sigma_i B^f = \frac{\sigma_i(\vec{\kappa})\Gamma^f(\vec{\kappa})}{\Gamma_H(\vec{\kappa})}$$

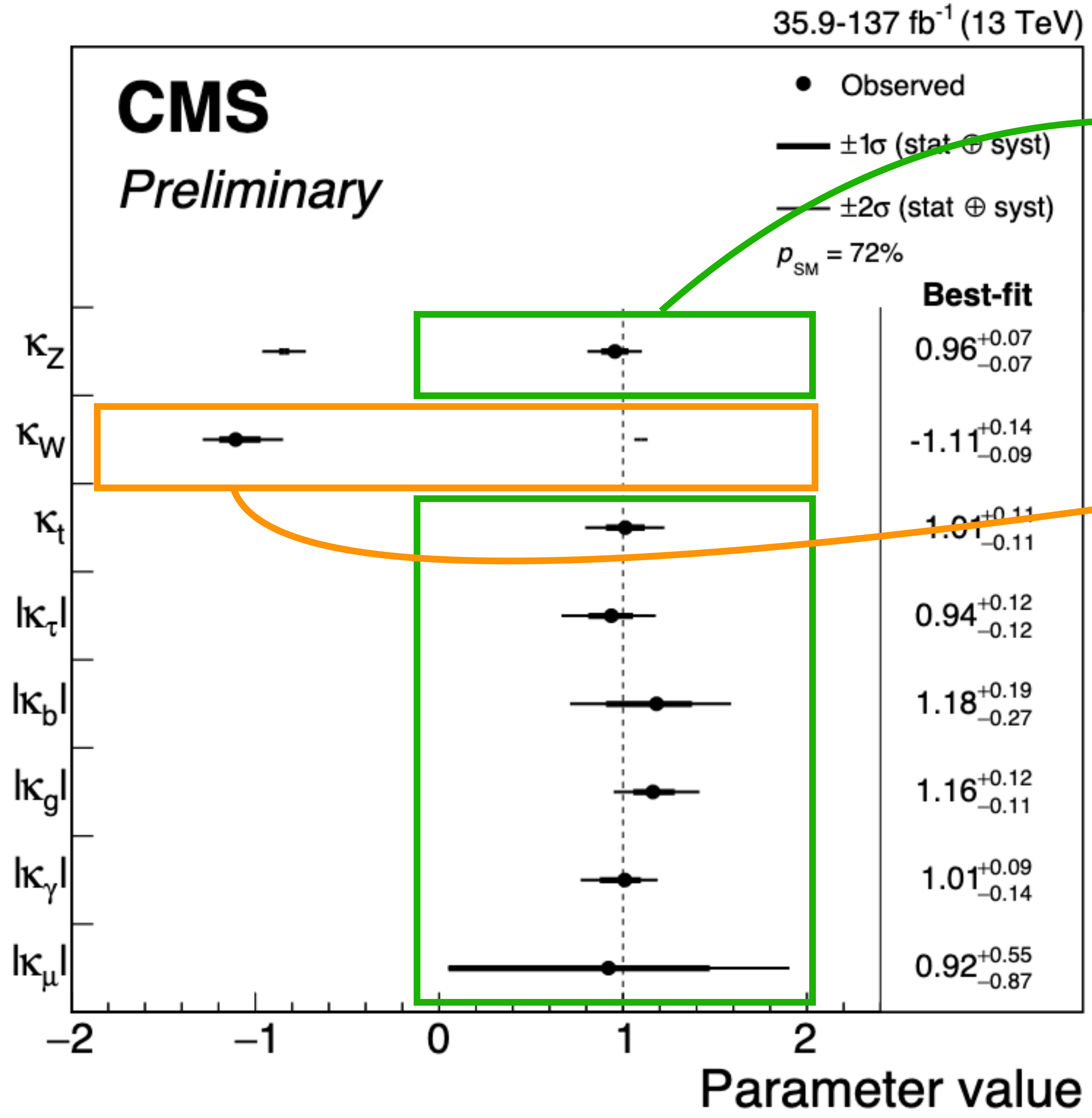
$\Gamma_H(\vec{\kappa})$: total width of the Higgs boson

$\Gamma^f(\vec{\kappa})$: partial width of the decay to the final state f

Coupling modifiers $\vec{\kappa}$ to parametrize deviations in HVV and Hff couplings from the SM predictions:

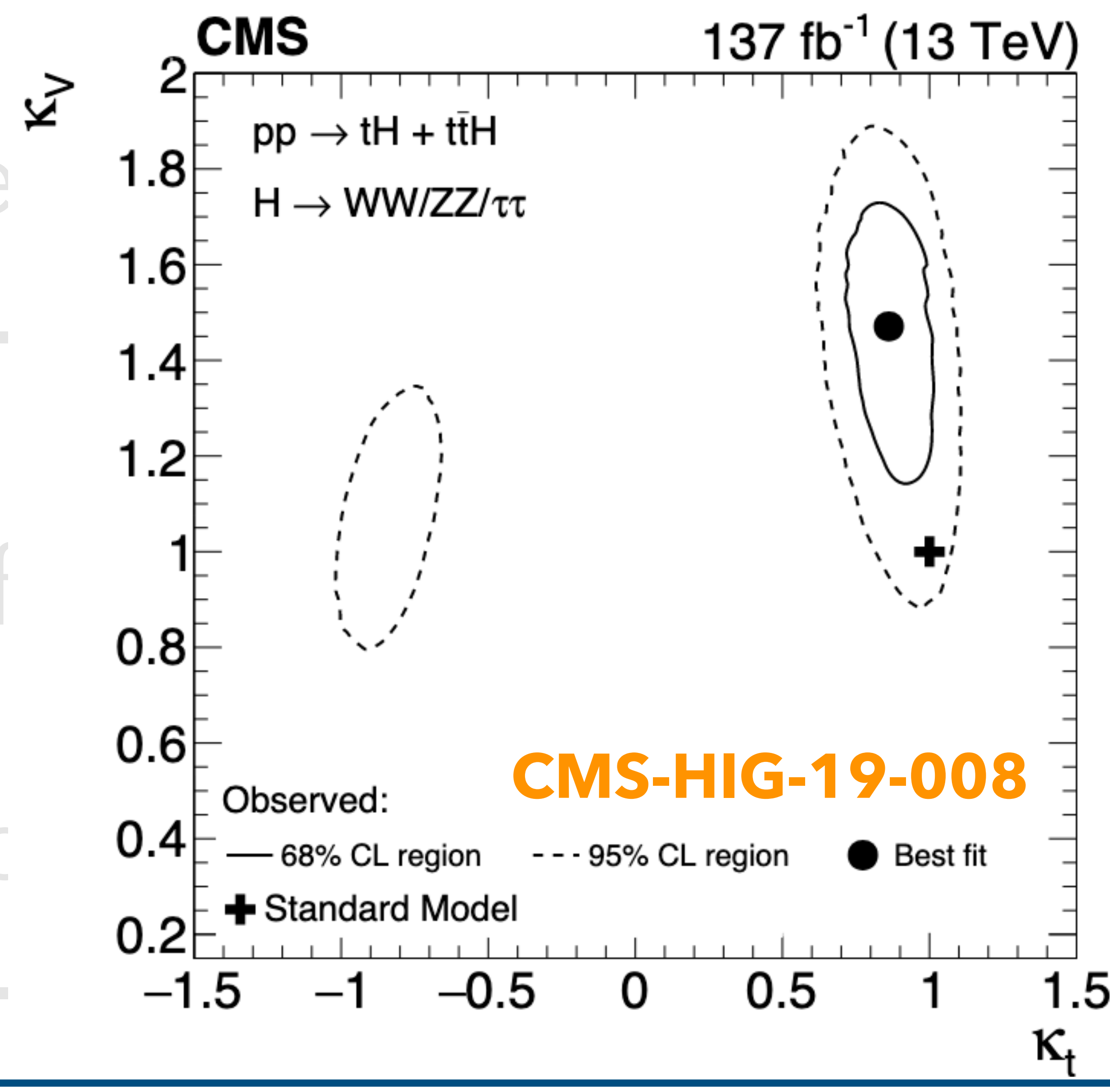
$$\kappa_j^2 = \sigma_j/\sigma_j^{SM} \quad \text{or} \quad \kappa_j^2 = \Gamma^j/\Gamma^j_{SM}$$

H boson couplings: κ-framework



All the measurements agree with the SM expectations ($\kappa_j = 1$)

The κ_W best-fit value is negative due to the interference between tH production diagrams



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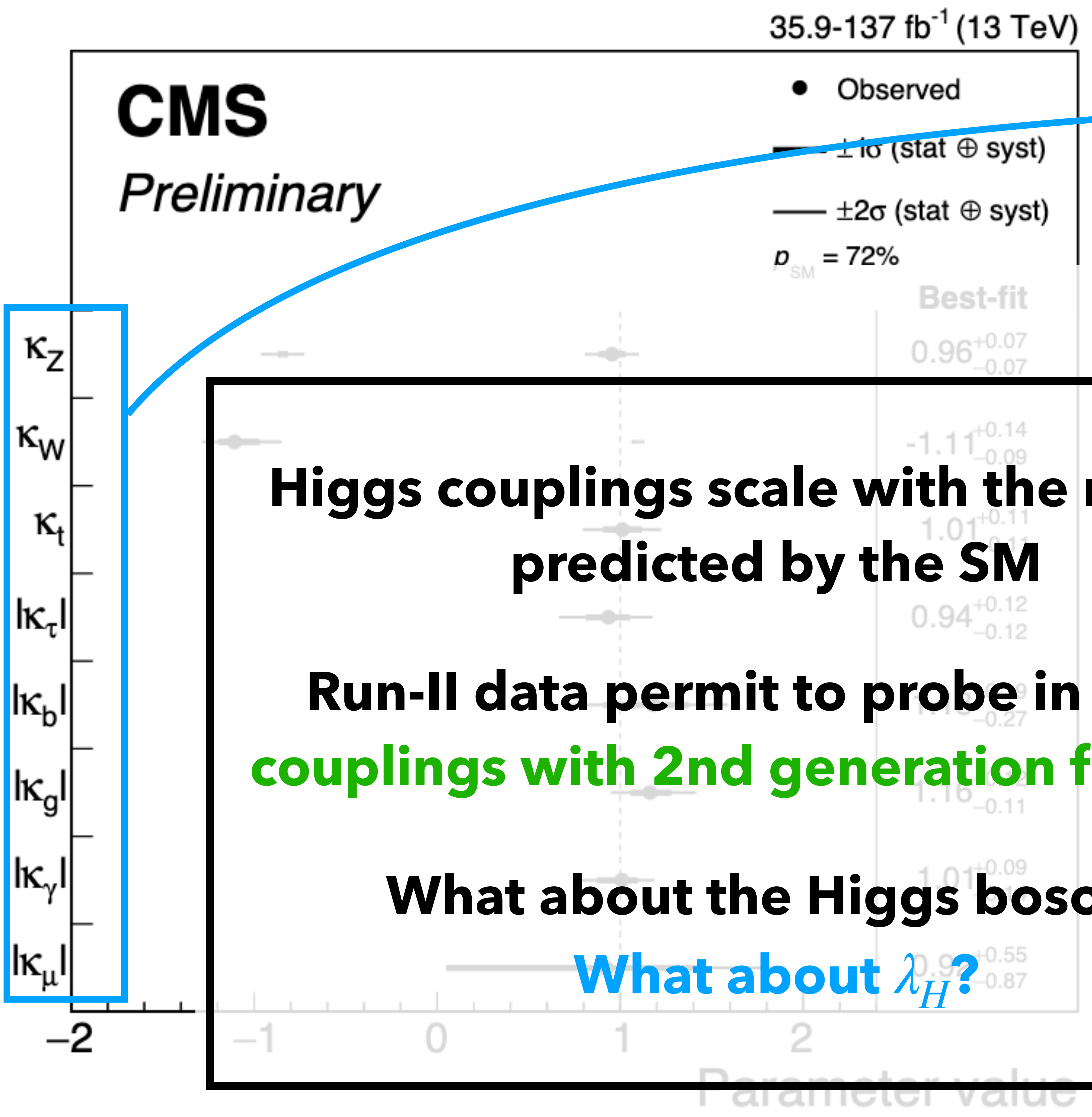
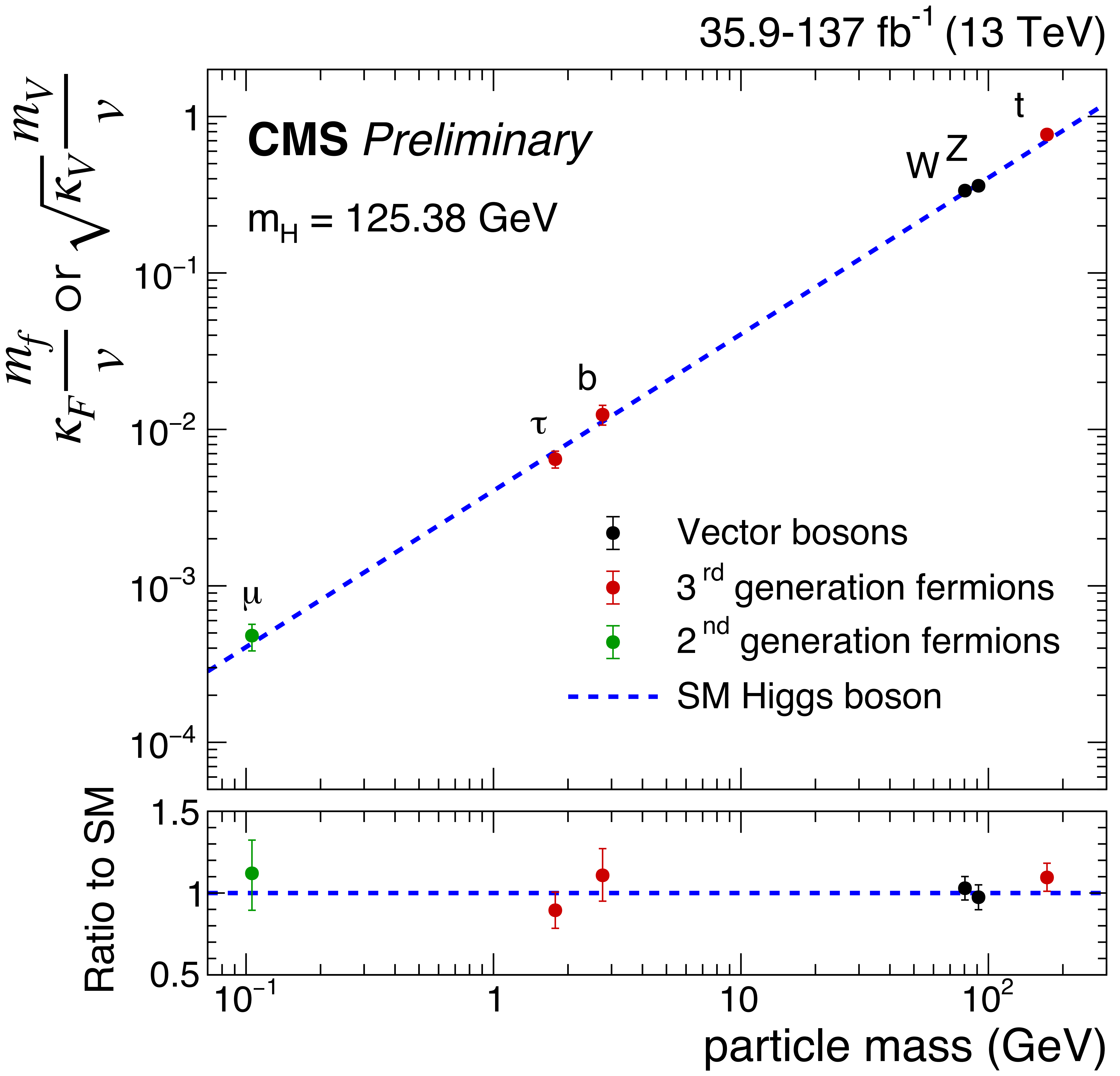


Higgs couplings scale with the mass as predicted by the SM

Run-II data permit to probe in detail couplings with 2nd generation fermions

What about the Higgs boson?

What about λ_H?



H boson self-coupling

Constraint on $\kappa_\lambda = \lambda_{HHH}/\lambda_{\rm SM}$ from single-Higgs decay channels via modifications of the production cross sections and decay widths from NLO electroweak corrections

Inclusive production and decay rates scale as[1]

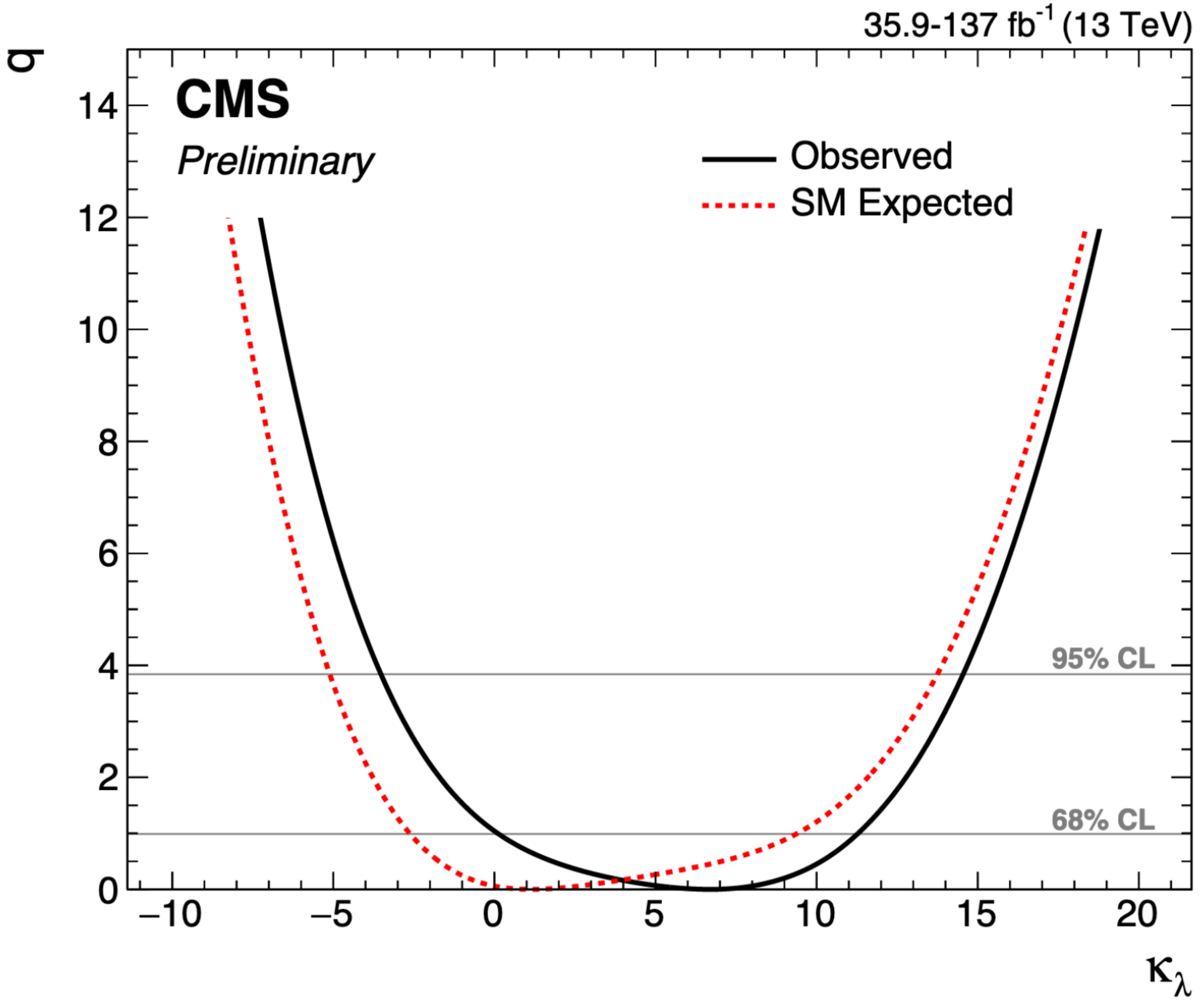
$$\mu_i(\kappa_{\rm V},\kappa_{\rm F},\kappa_\lambda) = Z_{\rm H}^{\rm BSM}(\kappa_\lambda)\left[S_i(\kappa_{\rm V},\kappa_{\rm F}) + K_{\rm BSM}(1-\kappa_\lambda)\right].$$

$$\mu^f(\kappa_{\rm V},\kappa_{\rm F},\kappa_\lambda) = \frac{S_f(\kappa_{\rm V},\kappa_{\rm F}) + (\kappa_\lambda - 1)C^f}{\sum_d \Gamma_d^{\rm SM}\left(S_d(\kappa_{\rm V},\kappa_{\rm F}) + (\kappa_\lambda - 1)C^d\right)}$$

Limits on κ_λ with $\kappa_V = \kappa_F = 1$:

$[-3.5, 14.5]$
([-5.1,13.7]) @95% CL

Additional scans with κ_V or κ_F floating in backup



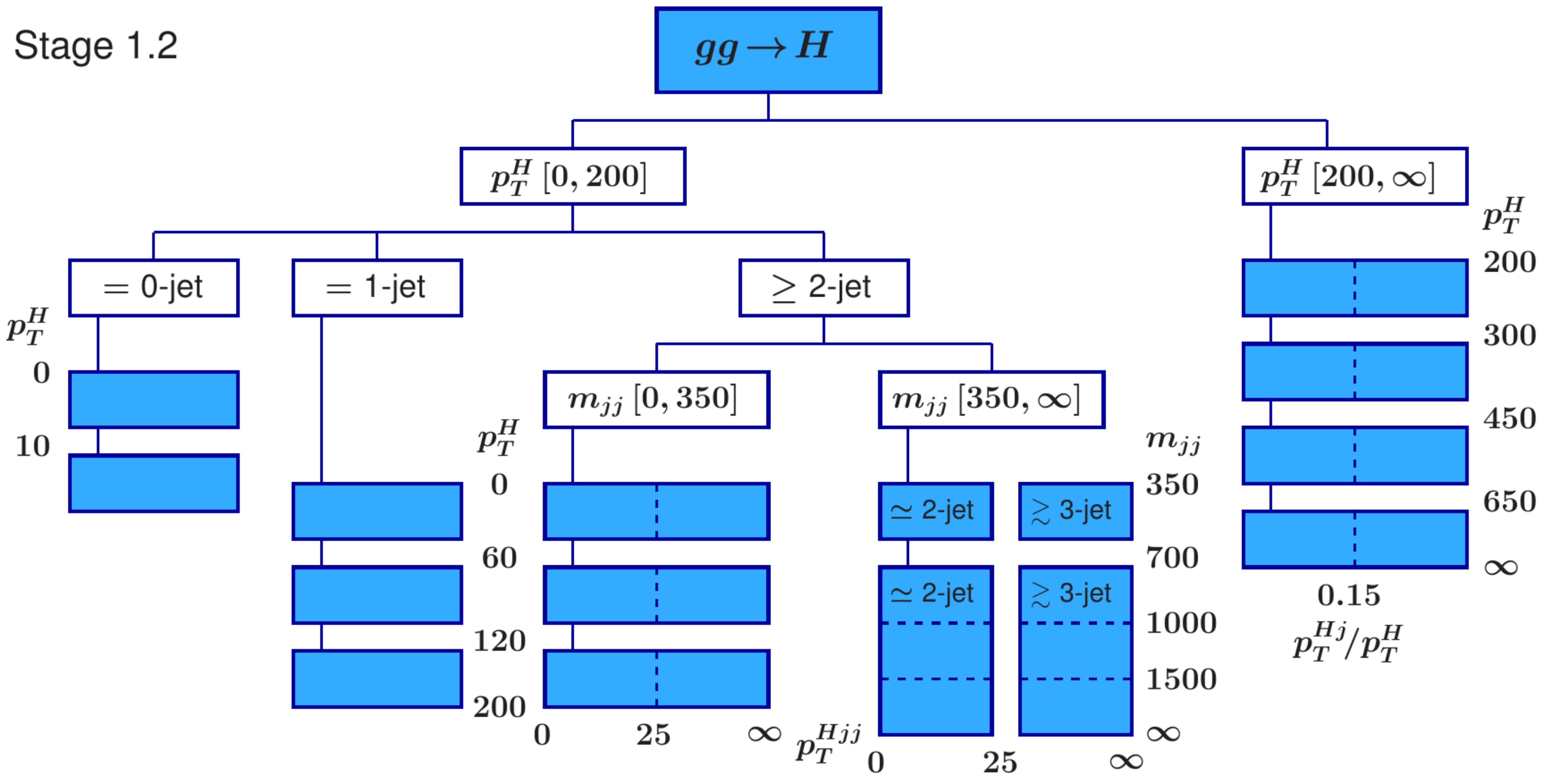
[1]: Details on the parametrisation in backup

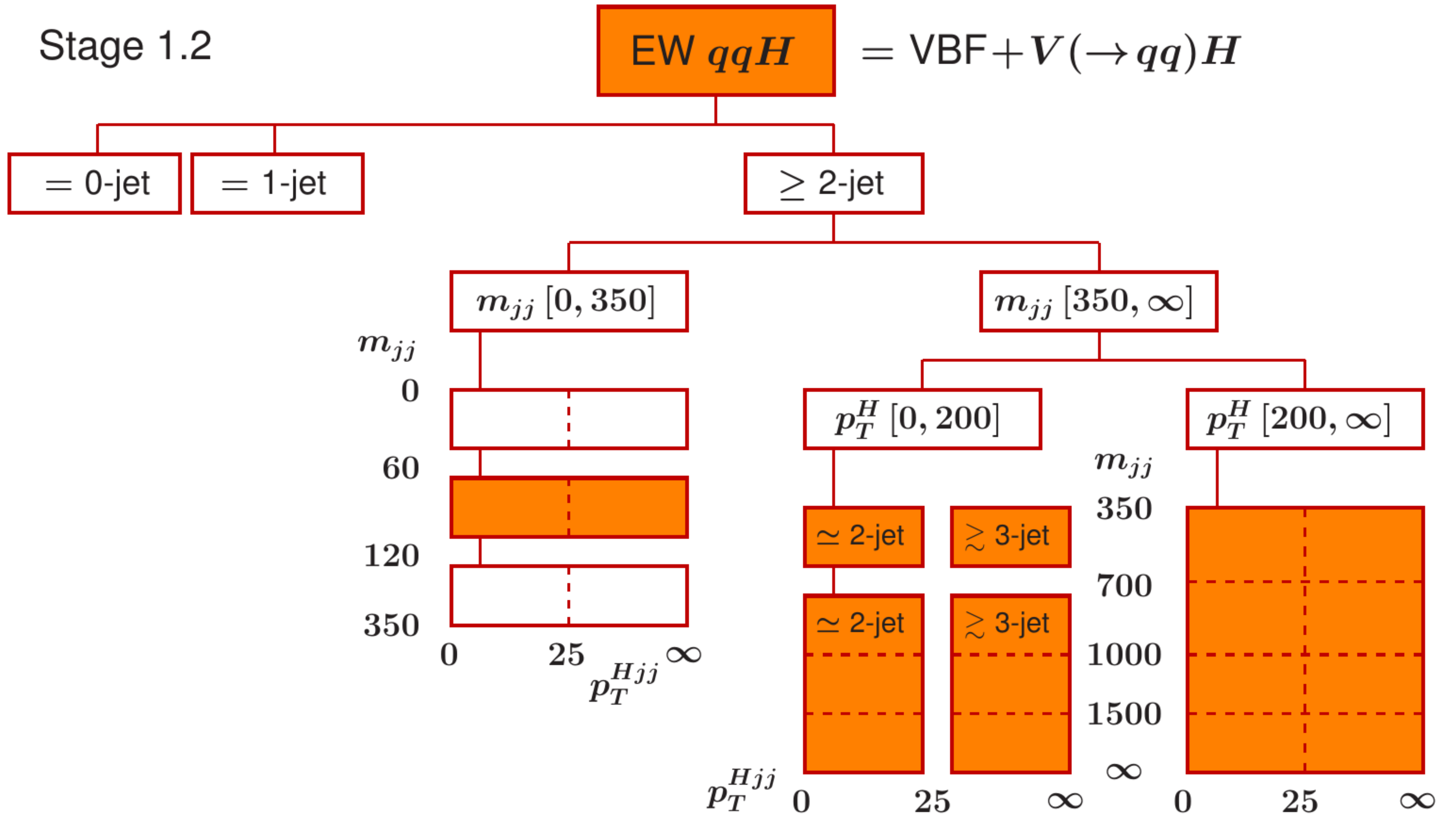
Simplified Template Cross Section framework

The primary goal of **STXS** framework is to **minimise the measurement dependence on theory predictions without losing sensitivity**

Coverage of the entire phase space and **specific regions** designed **to detect BSM effects**

In this analysis STXS bins used to set constraints on Effective Field Theory (EFT) operators





EFT couplings

Extend SM Lagrangian with higher-dim operators in the **HEL[1] model:**

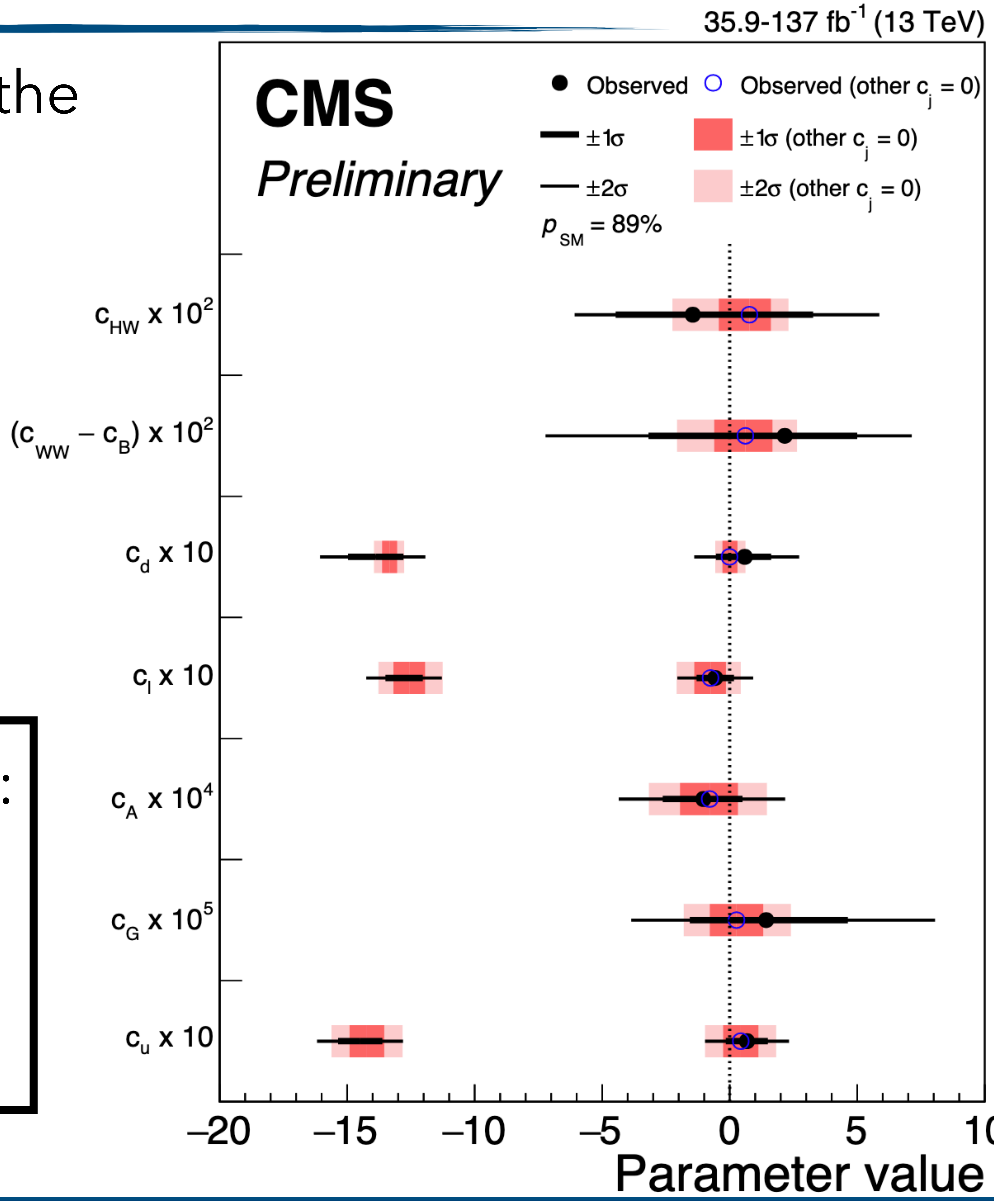
$$\mathcal{L}_{\mathrm{HEL}} = \mathcal{L}_{\mathrm{SM}} + \sum_j \mathcal{O}_j f_j / \Lambda^2$$

$$\Downarrow$$

$$\sigma_i^{\mathrm{EFT}} = \sigma_i^{\mathrm{SM}} + \sigma_i^{\mathrm{int}} + \sigma_i^{\mathrm{BSM}}$$

Scaling depending on $c_j = f_j/\Lambda^2$ for each STXS bin:

$$\mu_i(c_j) = \frac{\sigma_i^{\mathrm{EFT}}}{\sigma_i^{\mathrm{SM}}} = 1 + \sum_j A_j c_j + \sum_{jk} B_{jk} c_j c_k$$



[1]: Higgs Effective Lagrangian

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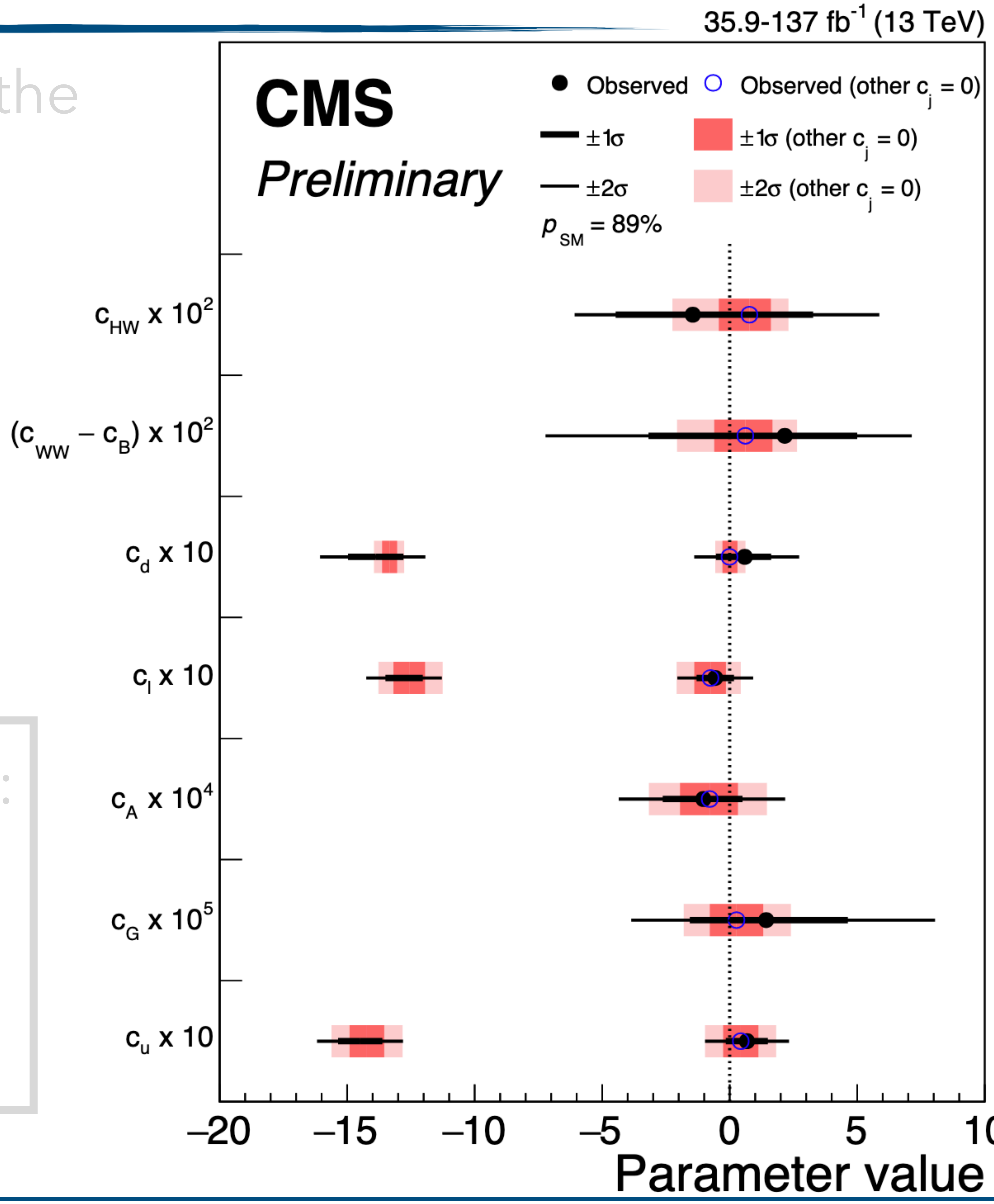
$\mathrm{H} \to \mu\mu$ and boosted $\mathrm{H} \to \mathrm{bb}$ analyses not considered

Eight EFT parameters measured simultaneously

Parameters related to **leading CP-even terms**

Stringent constraints on HEL parameters



[1]: Higgs Effective Lagrangian

Conclusions

The large statistics collected during Run-II opens the doors to *precision measurements era*

- Partial Run-II datasets used here, full Run-II analyses are ongoing and will be included in a future study
- Similar **statistical** and **systematic components of the uncertainty**, results will soon be limited by latter

Comprehensive characterization of the Higgs boson properties from combination of all decay channels

- Signal strength modifiers $\mu = 1.02 \pm 0.04(\mathrm{th}) \pm 0.04(\mathrm{exp}) \pm 0.04(\mathrm{stat})$
- Study Higgs couplings from κ-framework measurements and expected scaling with the mass is observed
- Interpretation of STXS measurements in EFT: most powerful constraints on HEL parameters to date

Full Run-II combination (from CMS and ATLAS+CMS) will enhance the precision of these results…

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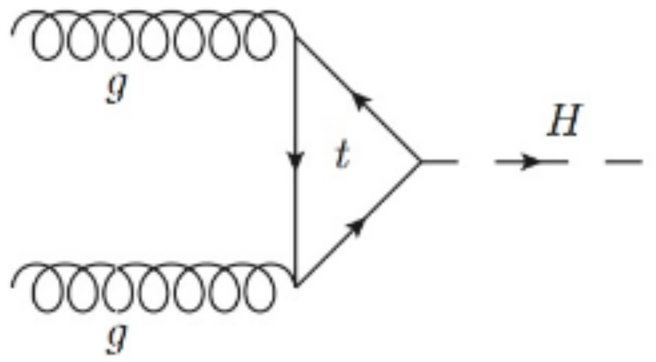
Full Run-II combination (from CMS and ATLAS+CMS) will enhance the precision of these results…

… and possibly unveil new physics!

BACKUP SLIDES

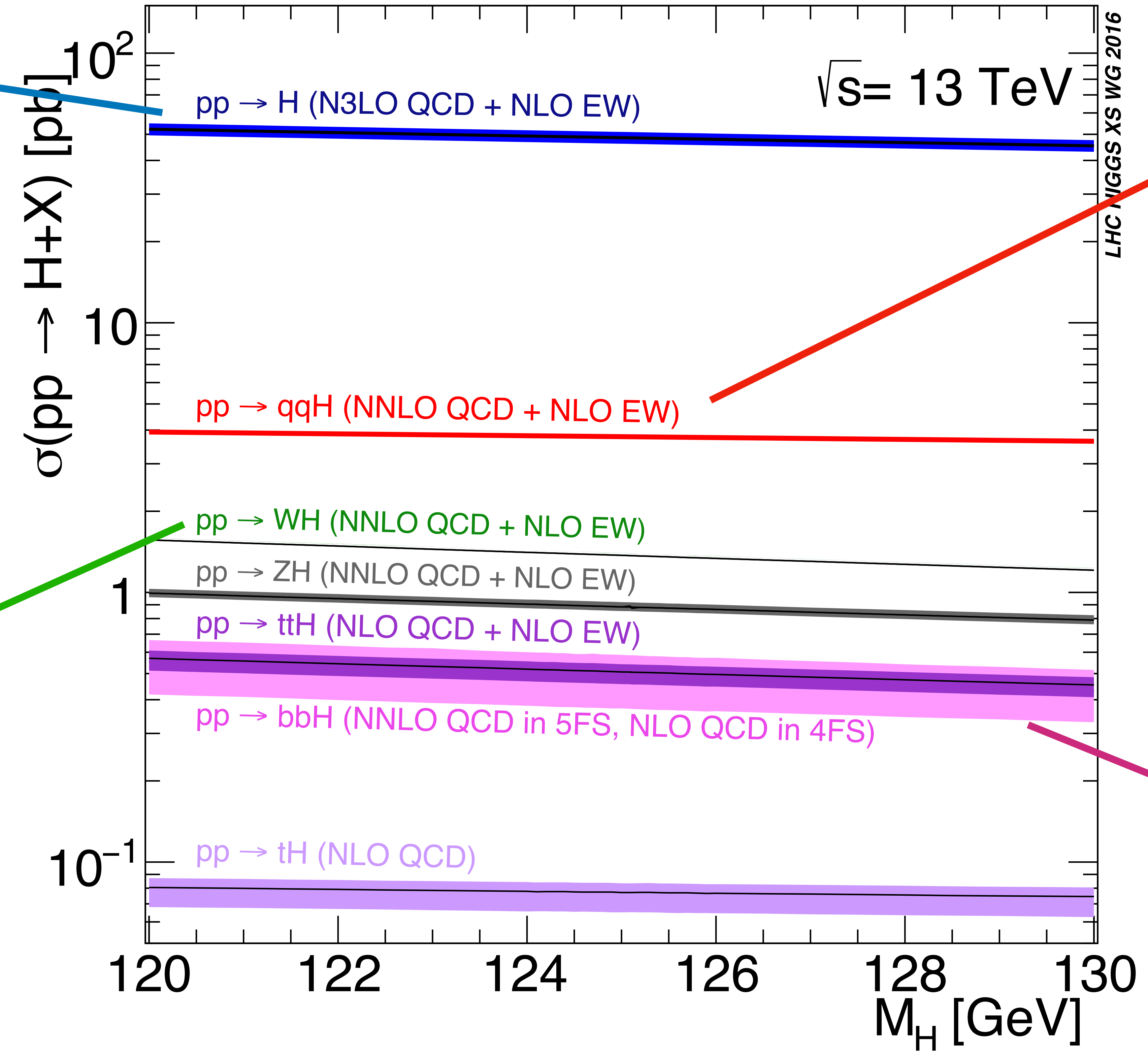
Higgs boson production at LHC

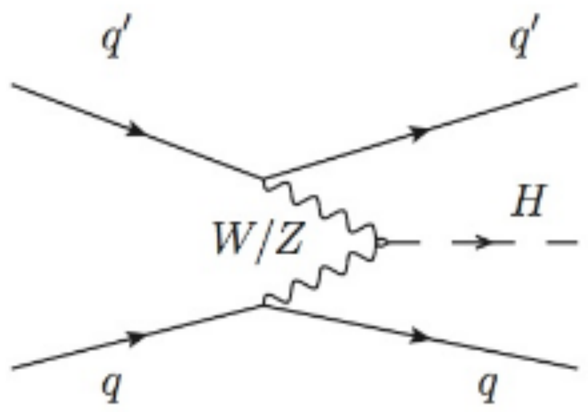


ggH

$\sigma \times \mathscr{B}(H \to WW) = 9.5$ pb

$\sigma \times \mathscr{B}(H \to ZZ) = 1.27$ pb

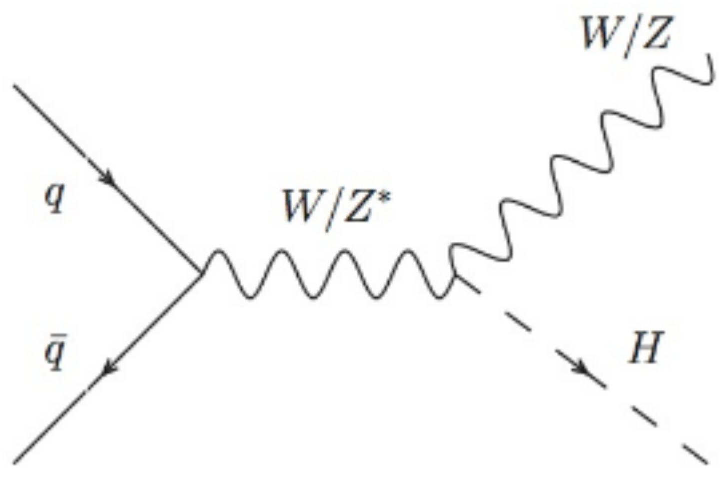




qqH, VBF

$\sigma \times \mathscr{B}(H \to WW) = 0.8$ pb

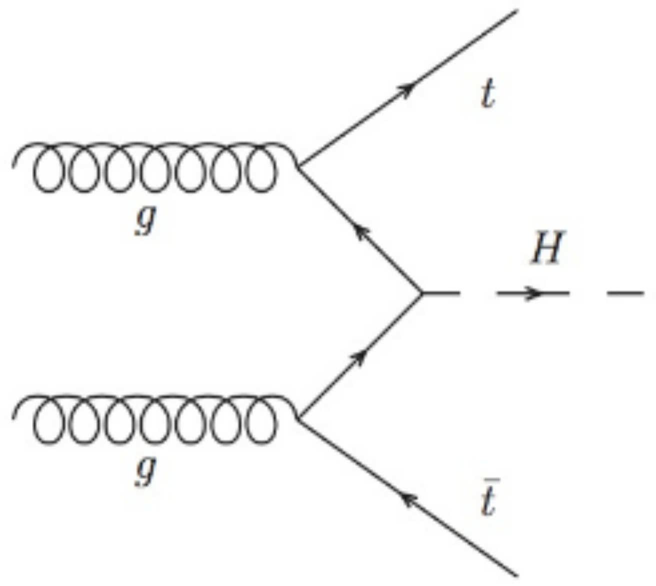
$\sigma \times \mathscr{B}(H \to ZZ) = 0.1$ pb



VH

$\sigma \times \mathscr{B}(H \to WW) = 0.5$ pb

$\sigma \times \mathscr{B}(H \to ZZ) = 0.06$ pb



ttH

$\sigma \times \mathscr{B}(H \to WW) = 0.1$ pb

$\sigma \times \mathscr{B}(H \to ZZ) = 0.01$ pb

The input analyses & categories

References in Backup

Analysis	Decay tags	Production tags	Luminosity (fb^{-1})	References
$\mathrm{H} \to \gamma\gamma$	$\gamma\gamma$	ggH, $p_{\mathrm{T}}(\mathrm{H}) \times$ N-jet bins VBF, $p_{\mathrm{T}}(\mathrm{H}\,jj)$ bins	77.4	[53]
		ttH	35.9, 41.5	[54], [55]
$\mathrm{H} \to \mathrm{ZZ}^{(*)} \to 4\ell$	4μ, $2e2\mu/2\mu2e$, 4e	ggH, $p_{\mathrm{T}}(\mathrm{H}) \times$ N-jet bins VBF, m_{jj} bins VH hadronic VH leptonic, $p_{\mathrm{T}}(\mathrm{V})$ bins ttH	137	[56]
$\mathrm{H} \to \mathrm{WW}^{(*)} \to \ell\nu\ell\nu$	$e\mu/\mu e$ $ee+\mu\mu$ $e\mu$+jj 3ℓ 4ℓ	ggH $\leq$ 2-jets VBF ggH $\leq$ 1-jet VH hadronic WH leptonic ZH leptonic	35.9	[57]
$\mathrm{H} \to \tau\tau$	$e\mu, e\tau_{\mathrm{h}}, \mu\tau_{\mathrm{h}}, \tau_{\mathrm{h}}\tau_{\mathrm{h}}$	ggH, $p_{\mathrm{T}}(\mathrm{H}) \times$ N-jet bins VH hadronic VBF	77.4	[58]
		VH, high-$p_{\mathrm{T}}(\mathrm{V})$	35.9	[59]
$\mathrm{H} \to \mathrm{bb}$	$\mathrm{W}(\ell\nu)\mathrm{H(bb)}$ $\mathrm{Z}(\nu\nu)\mathrm{H(bb)}, \mathrm{Z}(\ell\ell)\mathrm{H(bb)}$	WH leptonic ZH leptonic	35.9, 41.5	[60], [61]
	bb	ttH, $\mathrm{t\bar{t}} \to 0, 1, 2\ell +$ jets	77.4	[62]
		ggH, high-$p_{\mathrm{T}}(\mathrm{H})$ bins	35.9	[63]
ttH production with $\mathrm{H} \to$ leptons	$2\ell ss, 3\ell, 4\ell$, $1\ell+2\tau_{\mathrm{h}}, 2\ell ss+1\tau_{\mathrm{h}}, 3\ell+1\tau_{\mathrm{h}}$	ttH	35.9, 41.5	[64], [65]
$\mathrm{H} \to \mu\mu$	$\mu\mu$	ggH VBF	35.9	[66]

	Luminosity (fb^{-1})	References
$H \to \gamma\gamma$	77	CMS-PAS-HIG-18-029 CMS-PAS-HIG-18-018
$H \to ZZ^* \to 4\ell$	137	CMS-PAS-HIG-19-001
$H \to WW$	36	Phys. Lett. B 791 (2019) 96
$H \to bb$	36 (ggH) - 77 (others)	Phys. Rev. Lett. 121, 121801 (2018) CMS-PAS-HIG-18-030 Phys.Rev. Lett. 120, 071802 (2018)
$H \to \tau\tau$	77	CMS-PAS-HIG-18-032 JHEP 06 (2019) 093
ttH multilepton	77	CMS-PAS-HIG-18-019
$H \to \mu\mu$	36	Phys. Rev. Lett. 122, 021801 (2019)

Signal strength modifiers

Production μ_i			
		Uncertainty	
Parameters	Best-fit	Stat.	Syst.
μ_{ggH}	$1.04^{+0.09}_{-0.09}$ $\left(^{+0.09}_{-0.08}\right)$	$^{+0.05}_{-0.05}$ $\left(^{+0.05}_{-0.05}\right)$	$^{+0.08}_{-0.07}$ $\left(^{+0.07}_{-0.07}\right)$
μ_{VBF}	$0.75^{+0.19}_{-0.17}$ $\left(^{+0.20}_{-0.19}\right)$	$^{+0.16}_{-0.15}$ $\left(^{+0.17}_{-0.16}\right)$	$^{+0.10}_{-0.08}$ $\left(^{+0.11}_{-0.10}\right)$
μ_{WH}	$1.46^{+0.37}_{-0.35}$ $\left(^{+0.35}_{-0.34}\right)$	$^{+0.29}_{-0.28}$ $\left(^{+0.29}_{-0.28}\right)$	$^{+0.22}_{-0.21}$ $\left(^{+0.20}_{-0.19}\right)$
μ_{ZH}	$0.98^{+0.31}_{-0.30}$ $\left(^{+0.30}_{-0.29}\right)$	$^{+0.26}_{-0.25}$ $\left(^{+0.25}_{-0.25}\right)$	$^{+0.17}_{-0.16}$ $\left(^{+0.17}_{-0.15}\right)$
μ_{ttH}	$1.14^{+0.21}_{-0.20}$ $\left(^{+0.20}_{-0.18}\right)$	$^{+0.13}_{-0.13}$ $\left(^{+0.12}_{-0.12}\right)$	$^{+0.17}_{-0.15}$ $\left(^{+0.15}_{-0.13}\right)$

Decay μ^f			
		Uncertainty	
Parameters	Best-fit	Stat.	Syst.
$\mu^{\gamma\gamma}$	$1.07^{+0.12}_{-0.10}$ $\left(^{+0.11}_{-0.10}\right)$	$^{+0.08}_{-0.08}$ $\left(^{+0.08}_{-0.08}\right)$	$^{+0.08}_{-0.07}$ $\left(^{+0.07}_{-0.06}\right)$
μ^{ZZ}	$0.93^{+0.10}_{-0.09}$ $\left(^{+0.11}_{-0.10}\right)$	$^{+0.07}_{-0.07}$ $\left(^{+0.08}_{-0.07}\right)$	$^{+0.07}_{-0.06}$ $\left(^{+0.07}_{-0.06}\right)$
μ^{WW}	$1.20^{+0.16}_{-0.15}$ $\left(^{+0.14}_{-0.13}\right)$	$^{+0.09}_{-0.09}$ $\left(^{+0.09}_{-0.09}\right)$	$^{+0.13}_{-0.12}$ $\left(^{+0.11}_{-0.10}\right)$
$\mu^{\tau\tau}$	$0.80^{+0.17}_{-0.16}$ $\left(^{+0.18}_{-0.17}\right)$	$^{+0.10}_{-0.10}$ $\left(^{+0.10}_{-0.10}\right)$	$^{+0.14}_{-0.13}$ $\left(^{+0.15}_{-0.14}\right)$
μ^{bb}	$1.11^{+0.20}_{-0.19}$ $\left(^{+0.20}_{-0.19}\right)$	$^{+0.13}_{-0.13}$ $\left(^{+0.12}_{-0.12}\right)$	$^{+0.16}_{-0.15}$ $\left(^{+0.15}_{-0.14}\right)$
$\mu^{\mu\mu}$	$0.90^{+1.29}_{-1.28}$ $\left(^{+1.27}_{-1.26}\right)$	$^{+1.28}_{-1.27}$ $\left(^{+1.25}_{-1.26}\right)$	$^{+0.22}_{-0.13}$ $\left(^{+0.24}_{-0.06}\right)$

Signal strength modifiers

Decay mode	ggH				VBF				WH				ZH				ttH			
			Uncertainty				Uncertainty				Uncertainty				Uncertainty				Uncertainty	
	Best-fit		Stat.	Syst.	Best-fit		Stat.	Syst.	Best-fit		Stat.	Syst.	Best-fit		Stat.	Syst.	Best-fit		Stat.	Syst.
$H \to bb$	2.45	$^{+2.53}_{-2.35}$ $\left(^{+2.11}_{-1.95}\right)$	$^{+2.04}_{-2.01}$ $\left(^{+1.92}_{-1.91}\right)$	$^{+1.51}_{-1.22}$ $\left(^{+0.86}_{-0.34}\right)$	– (–)				1.27	$^{+0.42}_{-0.40}$ $\left(^{+0.42}_{-0.41}\right)$	$^{+0.32}_{-0.31}$ $\left(^{+0.33}_{-0.32}\right)$	$^{+0.27}_{-0.25}$ $\left(^{+0.27}_{-0.26}\right)$	0.93	$^{+0.33}_{-0.31}$ $\left(^{+0.32}_{-0.31}\right)$	$^{+0.27}_{-0.26}$ $\left(^{+0.26}_{-0.26}\right)$	$^{+0.19}_{-0.17}$ $\left(^{+0.19}_{-0.17}\right)$	1.13	$^{+0.33}_{-0.30}$ $\left(^{+0.32}_{-0.30}\right)$	$^{+0.16}_{-0.16}$ $\left(^{+0.16}_{-0.16}\right)$	$^{+0.29}_{-0.25}$ $\left(^{+0.28}_{-0.25}\right)$
$H \to \tau\tau$	0.39	$^{+0.38}_{-0.39}$ $\left(^{+0.39}_{-0.36}\right)$	$^{+0.16}_{-0.16}$ $\left(^{+0.16}_{-0.16}\right)$	$^{+0.35}_{-0.35}$ $\left(^{+0.36}_{-0.33}\right)$	1.05	$^{+0.30}_{-0.29}$ $\left(^{+0.31}_{-0.30}\right)$	$^{+0.25}_{-0.24}$ $\left(^{+0.25}_{-0.25}\right)$	$^{+0.18}_{-0.17}$ $\left(^{+0.18}_{-0.17}\right)$	3.01	$^{+1.65}_{-1.51}$ $\left(^{+1.52}_{-1.40}\right)$	$^{+1.37}_{-1.27}$ $\left(^{+1.27}_{-1.16}\right)$	$^{+0.92}_{-0.81}$ $\left(^{+0.82}_{-0.78}\right)$	1.53	$^{+1.60}_{-1.37}$ $\left(^{+1.45}_{-1.25}\right)$	$^{+1.41}_{-1.25}$ $\left(^{+1.32}_{-1.17}\right)$	$^{+0.75}_{-0.55}$ $\left(^{+0.59}_{-0.46}\right)$	0.81	$^{+0.74}_{-0.67}$ $\left(^{+0.72}_{-0.64}\right)$	$^{+0.57}_{-0.53}$ $\left(^{+0.57}_{-0.53}\right)$	$^{+0.46}_{-0.40}$ $\left(^{+0.43}_{-0.36}\right)$
$H \to WW$	1.28	$^{+0.20}_{-0.19}$ $\left(^{+0.17}_{-0.16}\right)$	$^{+0.11}_{-0.11}$ $\left(^{+0.11}_{-0.10}\right)$	$^{+0.17}_{-0.15}$ $\left(^{+0.14}_{-0.12}\right)$	0.63	$^{+0.65}_{-0.61}$ $\left(^{+0.61}_{-0.58}\right)$	$^{+0.58}_{-0.54}$ $\left(^{+0.55}_{-0.52}\right)$	$^{+0.30}_{-0.29}$ $\left(^{+0.27}_{-0.26}\right)$	2.85	$^{+2.11}_{-1.87}$ $\left(^{+1.48}_{-1.20}\right)$	$^{+1.78}_{-1.60}$ $\left(^{+1.33}_{-1.09}\right)$	$^{+1.13}_{-0.96}$ $\left(^{+0.64}_{-0.51}\right)$	0.90	$^{+1.77}_{-1.43}$ $\left(^{+1.67}_{-1.37}\right)$	$^{+1.70}_{-1.41}$ $\left(^{+1.61}_{-1.36}\right)$	$^{+0.50}_{-0.24}$ $\left(^{+0.43}_{-0.21}\right)$	0.93	$^{+0.48}_{-0.45}$ $\left(^{+0.45}_{-0.41}\right)$	$^{+0.37}_{-0.36}$ $\left(^{+0.35}_{-0.35}\right)$	$^{+0.30}_{-0.26}$ $\left(^{+0.27}_{-0.22}\right)$
$H \to ZZ$	0.98	$^{+0.12}_{-0.11}$ $\left(^{+0.13}_{-0.12}\right)$	$^{+0.09}_{-0.09}$ $\left(^{+0.10}_{-0.09}\right)$	$^{+0.08}_{-0.07}$ $\left(^{+0.08}_{-0.07}\right)$	0.57	$^{+0.46}_{-0.36}$ $\left(^{+0.57}_{-0.47}\right)$	$^{+0.44}_{-0.35}$ $\left(^{+0.52}_{-0.44}\right)$	$^{+0.15}_{-0.09}$ $\left(^{+0.23}_{-0.14}\right)$	1.10	$^{+0.96}_{-0.74}$ $\left(^{+0.99}_{-0.73}\right)$	$^{+0.94}_{-0.74}$ $\left(^{+0.96}_{-0.72}\right)$	$^{+0.19}_{-0.10}$ $\left(^{+0.21}_{-0.11}\right)$					0.25	$^{+1.03}_{-0.25}$ $\left(^{+1.12}_{-0.67}\right)$	$^{+1.00}_{-0.25}$ $\left(^{+1.10}_{-0.67}\right)$	$^{+0.21}_{-0.00}$ $\left(^{+0.22}_{-0.06}\right)$
$H \to \gamma\gamma$	1.09	$^{+0.15}_{-0.14}$ $\left(^{+0.14}_{-0.13}\right)$	$^{+0.11}_{-0.11}$ $\left(^{+0.11}_{-0.11}\right)$	$^{+0.10}_{-0.08}$ $\left(^{+0.09}_{-0.07}\right)$	0.77	$^{+0.37}_{-0.29}$ $\left(^{+0.41}_{-0.36}\right)$	$^{+0.32}_{-0.27}$ $\left(^{+0.33}_{-0.32}\right)$	$^{+0.18}_{-0.09}$ $\left(^{+0.25}_{-0.18}\right)$	– (–)				– (–)				1.62	$^{+0.52}_{-0.43}$ $\left(^{+0.41}_{-0.35}\right)$	$^{+0.44}_{-0.40}$ $\left(^{+0.39}_{-0.35}\right)$	$^{+0.27}_{-0.14}$ $\left(^{+0.15}_{-0.07}\right)$
$H \to \mu\mu$	0.31	$^{+1.82}_{-1.81}$ $\left(^{+1.78}_{-1.79}\right)$	$^{+1.80}_{-1.80}$ $\left(^{+1.76}_{-1.79}\right)$	$^{+0.22}_{-0.22}$ $\left(^{+0.28}_{-0.07}\right)$	3.18	$^{+8.22}_{-7.93}$ $\left(^{+8.13}_{-7.95}\right)$	$^{+7.99}_{-7.90}$ $\left(^{+8.01}_{-7.88}\right)$	$^{+1.93}_{-0.76}$ $\left(^{+1.41}_{-1.05}\right)$	– (–)				– (–)				– (–)			

H boson couplings: κ-framework

Coupling modifiers κ_i

Parameters	Best-fit	Uncertainty Stat.	Uncertainty Syst.
κ_Z	$0.96^{+0.07}_{-0.07}$ $\left(^{+0.08}_{-0.08}\right)$	$^{+0.06}_{-0.06}$ $\left(^{+0.06}_{-0.06}\right)$	$^{+0.04}_{-0.05}$ $\left(^{+0.05}_{-0.05}\right)$
κ_W	$-1.11^{+0.14}_{-0.09}$ $\left(^{+0.09}_{-0.09}\right)$	$^{+0.13}_{-0.07}$ $\left(^{+0.07}_{-0.07}\right)$	$^{+0.05}_{-0.06}$ $\left(^{+0.06}_{-0.06}\right)$
κ_t	$1.01^{+0.11}_{-0.11}$ $\left(^{+0.10}_{-0.10}\right)$	$^{+0.06}_{-0.06}$ $\left(^{+0.06}_{-0.06}\right)$	$^{+0.09}_{-0.08}$ $\left(^{+0.08}_{-0.08}\right)$
κ_τ	$0.94^{+0.12}_{-0.12}$ $\left(^{+0.12}_{-0.11}\right)$	$^{+0.08}_{-0.11}$ $\left(^{+0.08}_{-0.07}\right)$	$^{+0.09}_{-0.06}$ $\left(^{+0.09}_{-0.08}\right)$
κ_b	$1.18^{+0.19}_{-0.27}$ $\left(^{+0.17}_{-0.16}\right)$	$^{+0.14}_{-0.13}$ $\left(^{+0.13}_{-0.12}\right)$	$^{+0.13}_{-0.24}$ $\left(^{+0.11}_{-0.11}\right)$
κ_g	$1.16^{+0.12}_{-0.11}$ $\left(^{+0.11}_{-0.10}\right)$	$^{+0.08}_{-0.08}$ $\left(^{+0.07}_{-0.07}\right)$	$^{+0.08}_{-0.08}$ $\left(^{+0.08}_{-0.07}\right)$
κ_γ	$1.01^{+0.09}_{-0.14}$ $\left(^{+0.09}_{-0.08}\right)$	$^{+0.07}_{-0.07}$ $\left(^{+0.07}_{-0.07}\right)$	$^{+0.06}_{-0.12}$ $\left(^{+0.05}_{-0.05}\right)$
κ_μ	$0.92^{+0.55}_{-0.87}$ $\left(^{+0.52}_{-0.96}\right)$	$^{+0.54}_{-0.87}$ $\left(^{+0.51}_{-0.95}\right)$	$^{+0.10}_{-0.01}$ $\left(^{+0.08}_{-0.08}\right)$

Assuming only SM Higgs boson decays:

$$\sigma_i B^f = \frac{\sigma_i(\vec{\kappa})\Gamma^f(\vec{\kappa})}{\Gamma_H(\vec{\kappa})}$$

$\Gamma_H(\vec{\kappa})$: total width of the Higgs boson

$\Gamma^f(\vec{\kappa})$: partial width of the decay to the final state f

Coupling modifiers $\vec{\kappa}$ to parametrize deviations in HVV and Hff couplings from the SM predictions:

$$\kappa_j^2 = \sigma_j/\sigma_j^{SM} \quad \text{or} \quad \kappa_j^2 = \Gamma^j/\Gamma^j_{SM}$$

Extract $\mu_{i,j}\left(\kappa_\lambda\right)$

$$\mu^{\text{prod}}\left(\kappa_\lambda, C1\right) = \frac{\sigma^{\text{NLO}}}{\sigma^{\text{NLO}}_{\text{SM}}} = \frac{1 + \kappa_\lambda C_1 + \delta Z_H}{\left(1 - \left(\kappa_\lambda^2 - 1\right)\delta Z_H\right)\left(1 + C_1 + \delta Z_H\right)}$$

$$\mu_i^f = \mu_i \times \mu^f$$

$$\mu^{\text{decay}}\left(\kappa_\lambda, C_1^{\Gamma_{ZZ}}\right) = \frac{BR(H \to ZZ)}{BR(H \to ZZ)} = 1 + \frac{\left(\kappa_\lambda - 1\right)\left(C_1^{\Gamma_{ZZ}} - C_1^{\Gamma_{tot}}\right)}{1 + \left(\kappa_\lambda - 1\right) C_1^{\Gamma_{tot}}}$$

Extract $\mu_{i,j}\left(\kappa_\lambda\right)$

$$\mu^{\text{prod}}\left(\kappa_\lambda, C1\right) = \frac{\sigma^{\text{NLO}}}{\sigma^{\text{NLO}}_{\text{SM}}} = \frac{1+\kappa_\lambda C_1 + \delta Z_H}{\left(1-\left(\kappa_\lambda^2-1\right)\delta Z_H\right)\left(1+C_1+\delta Z_H\right)}$$

$$\mu_i^f = \mu_i \times \mu^f$$

$C_1^\Gamma[\%]$	$\gamma\gamma$	ZZ	WW	$f\bar{f}$	gg
on-shell H	0.49	0.83	0.73	0	0.66

$$C_1^{\Gamma_{tot}} = \sum_j \text{BR}_j^{\text{SM}} C_1^\Gamma(j) = 2.5 \times 10^{-3}$$

$$\mu^{\text{decay}}\left(\kappa_\lambda, C_1^{\Gamma_{ZZ}}\right) = \frac{BR(H\to ZZ)}{BR(H\to ZZ)} = 1 + \frac{\left(\kappa_\lambda - 1\right)\left(C_1^{\Gamma_{ZZ}} - C_1^{\Gamma_{tot}}\right)}{1+\left(\kappa_\lambda-1\right)C_1^{\Gamma_{tot}}}$$

Extract $\mu_{i,j}\left(\kappa_\lambda\right)$

$$\mu^{\text{prod}}\left(\kappa_\lambda, C1\right) = \frac{\sigma^{\text{NLO}}}{\sigma^{\text{NLO}}_{\text{SM}}} = \frac{1 + \kappa_\lambda C_1 + \delta Z_H}{\left(1 - \left(\kappa_\lambda^2 - 1\right)\delta Z_H\right)\left(1 + C_1 + \delta Z_H\right)}$$

$$\mu_i^f = \mu_i \times \mu^f$$

$$\kappa_\lambda = \frac{\lambda_3}{\lambda_3^{SM}}$$

$$C_1(p_n) = \frac{2\Re\left(\mathscr{M}^{0*}\mathscr{M}^1_{\lambda_3^{SM}}\right)}{\left|\mathscr{M}^0\right|^2}$$

$$\delta Z_H = -1.536 \times 10^{-3}$$

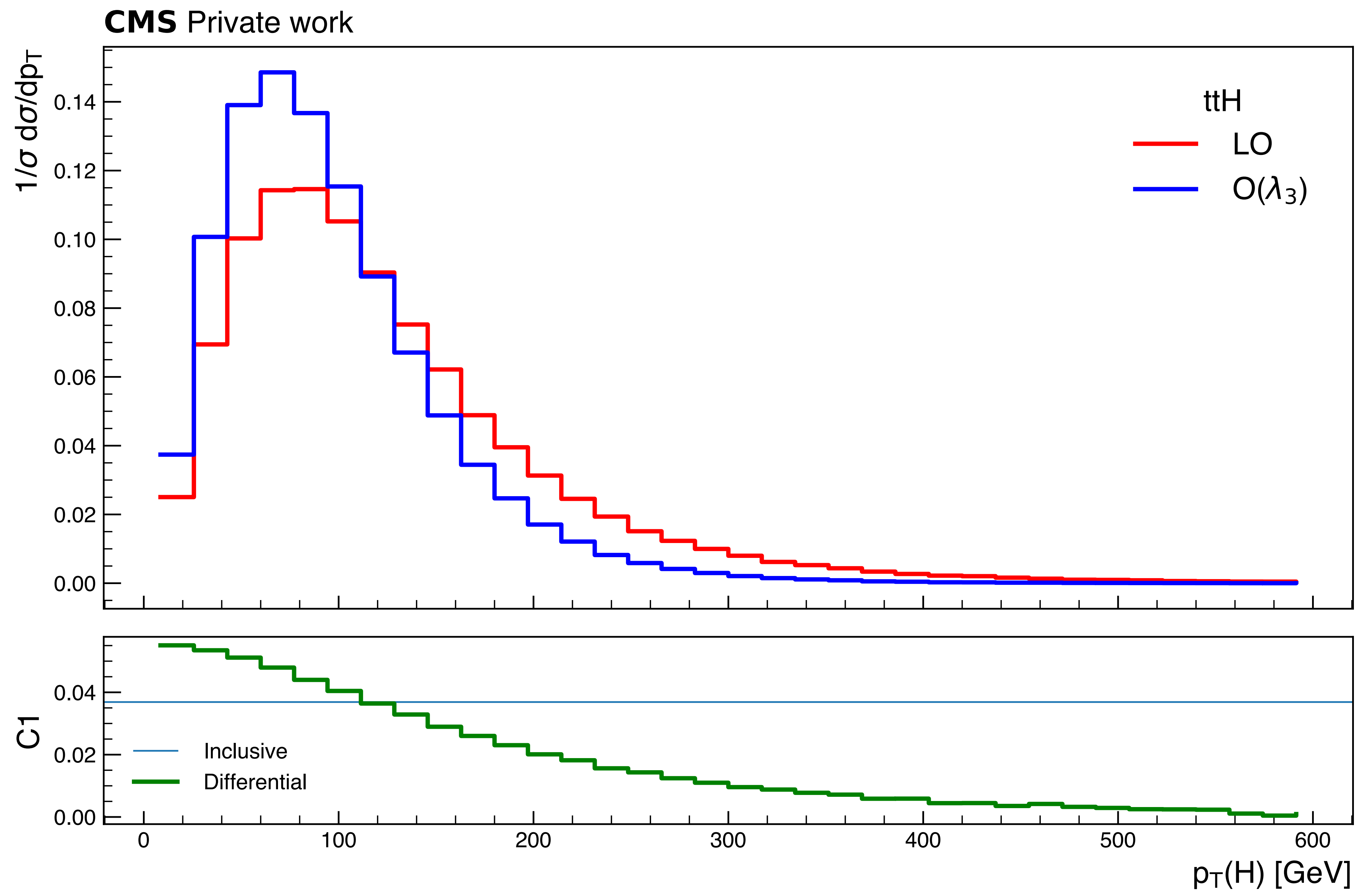
Depends both on the H boson production mode and on the kinematics

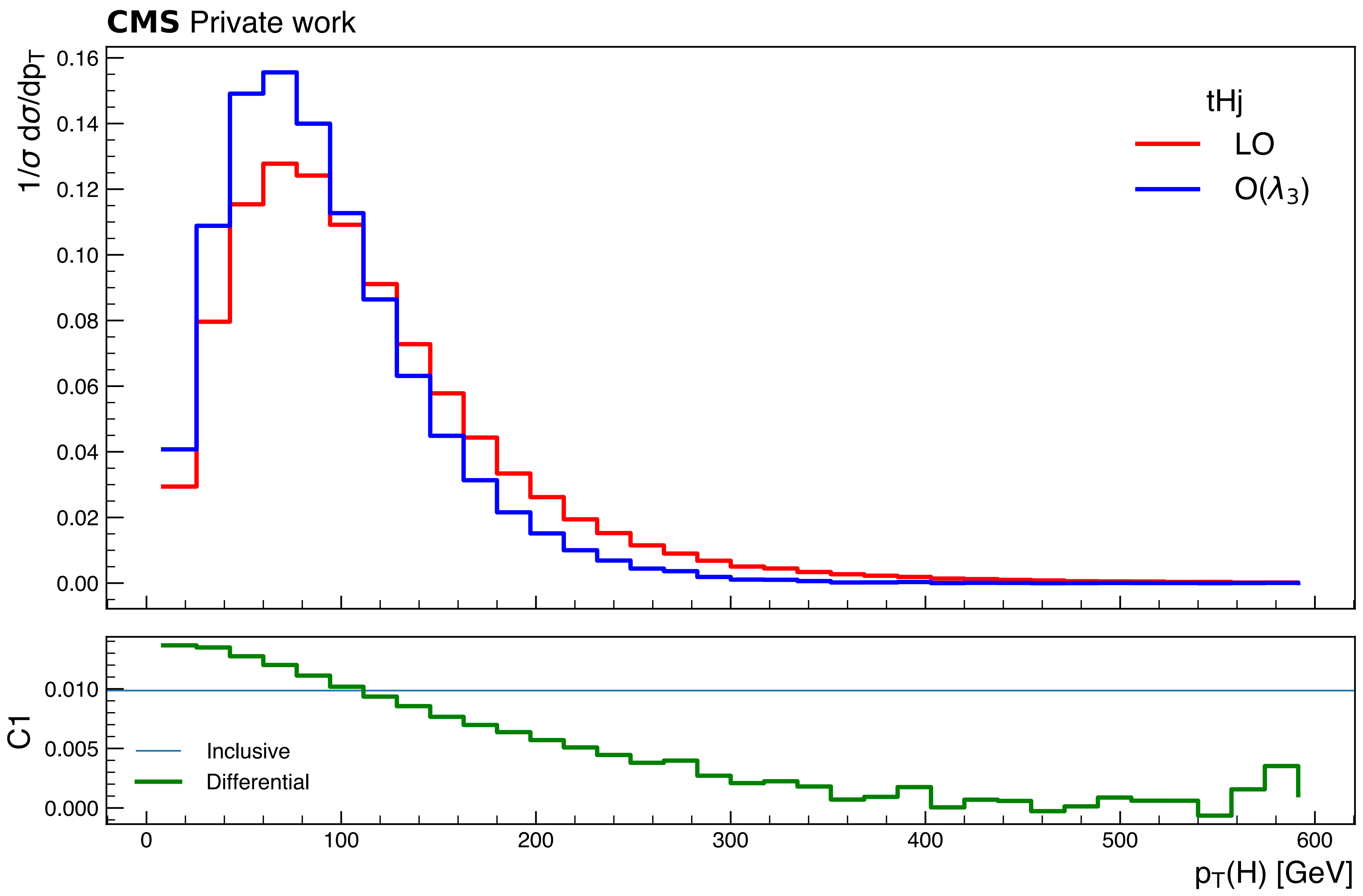
$$\mu^{\text{decay}}\left(\kappa_\lambda, C_1^{\Gamma_{ZZ}}\right) = \frac{BR(H \to ZZ)}{BR(H \to ZZ)} = 1 + \frac{\left(\kappa_\lambda - 1\right)\left(C_1^{\Gamma_{ZZ}} - C_1^{\Gamma_{tot}}\right)}{1 + \left(\kappa_\lambda - 1\right)C_1^{\Gamma_{tot}}}$$

Compute $C_1(p_n)$

While δZ_H is a universal quantity, $C_1(p_n)$ is process and kinematics dependent

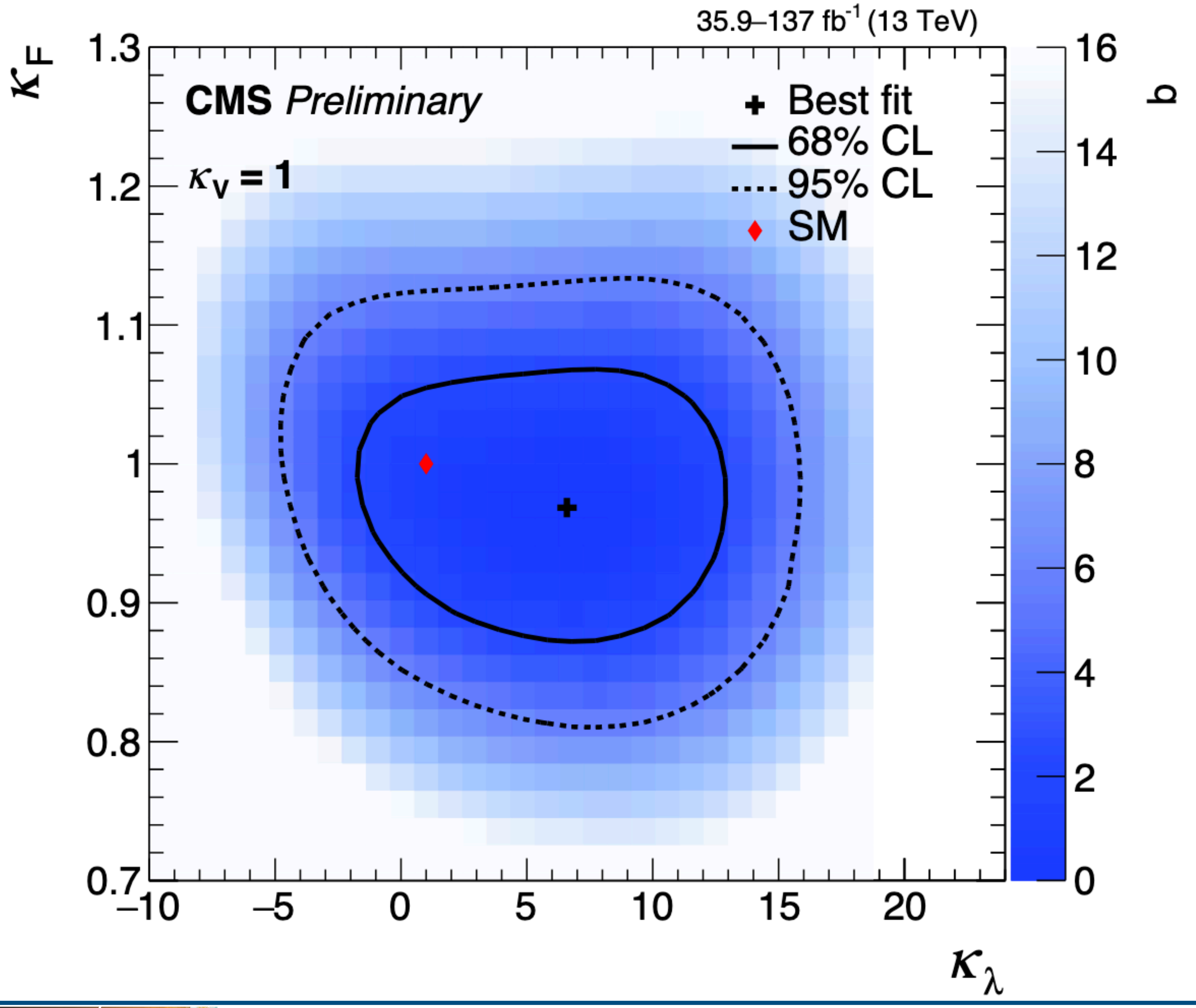
- MadGraph5 dedicated hhh-model and reweighing tool available
- Generate LO events (for each prod. mode) and reweigh to take into account NLO EW corrections
  - Extracted on an event-by-event basis: $C_1 = \mathrm{xsec}_{\mathcal{O}(\lambda_3)}/\mathrm{xsec}_{\mathrm{LO}}$

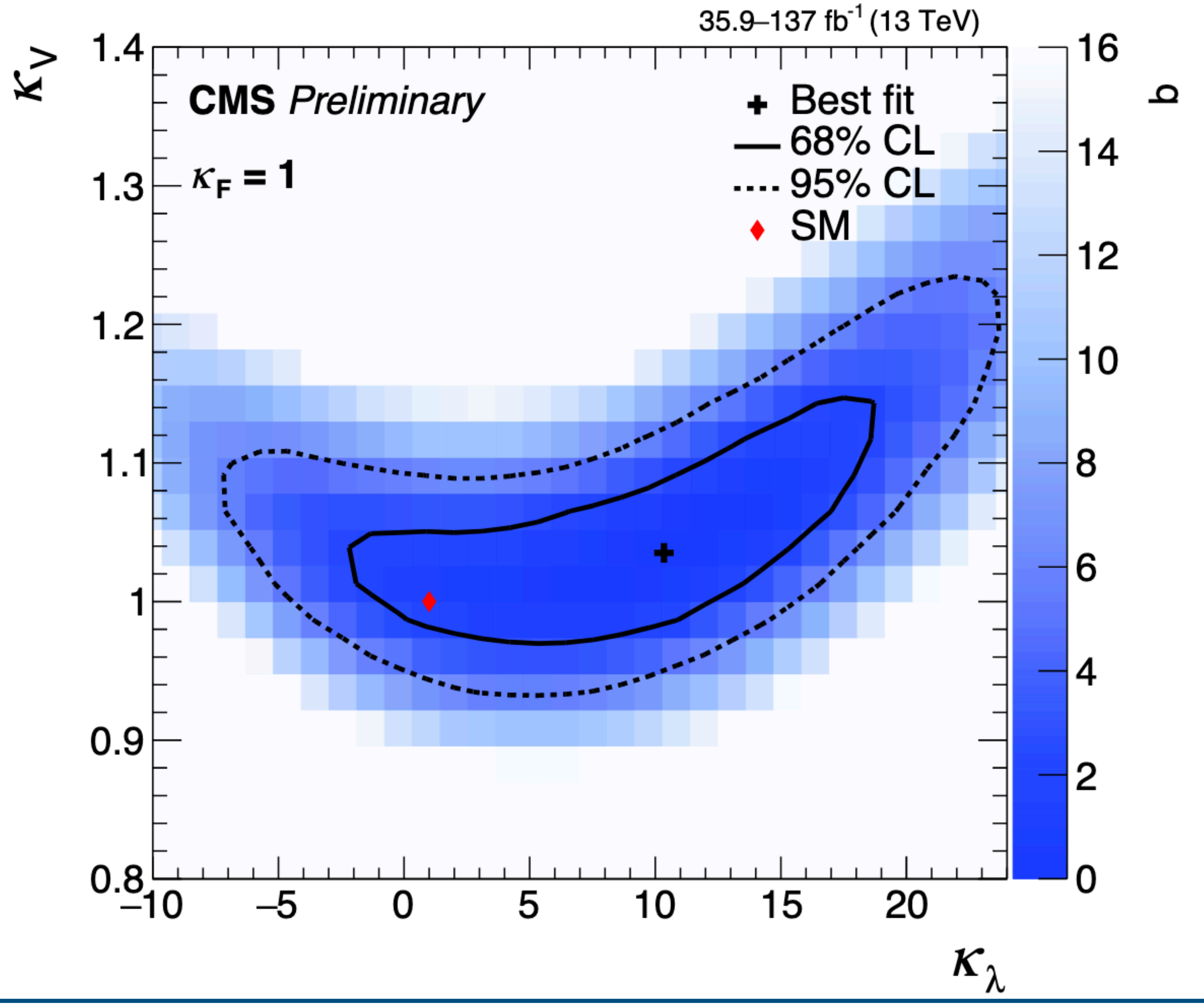




H boson self-coupling

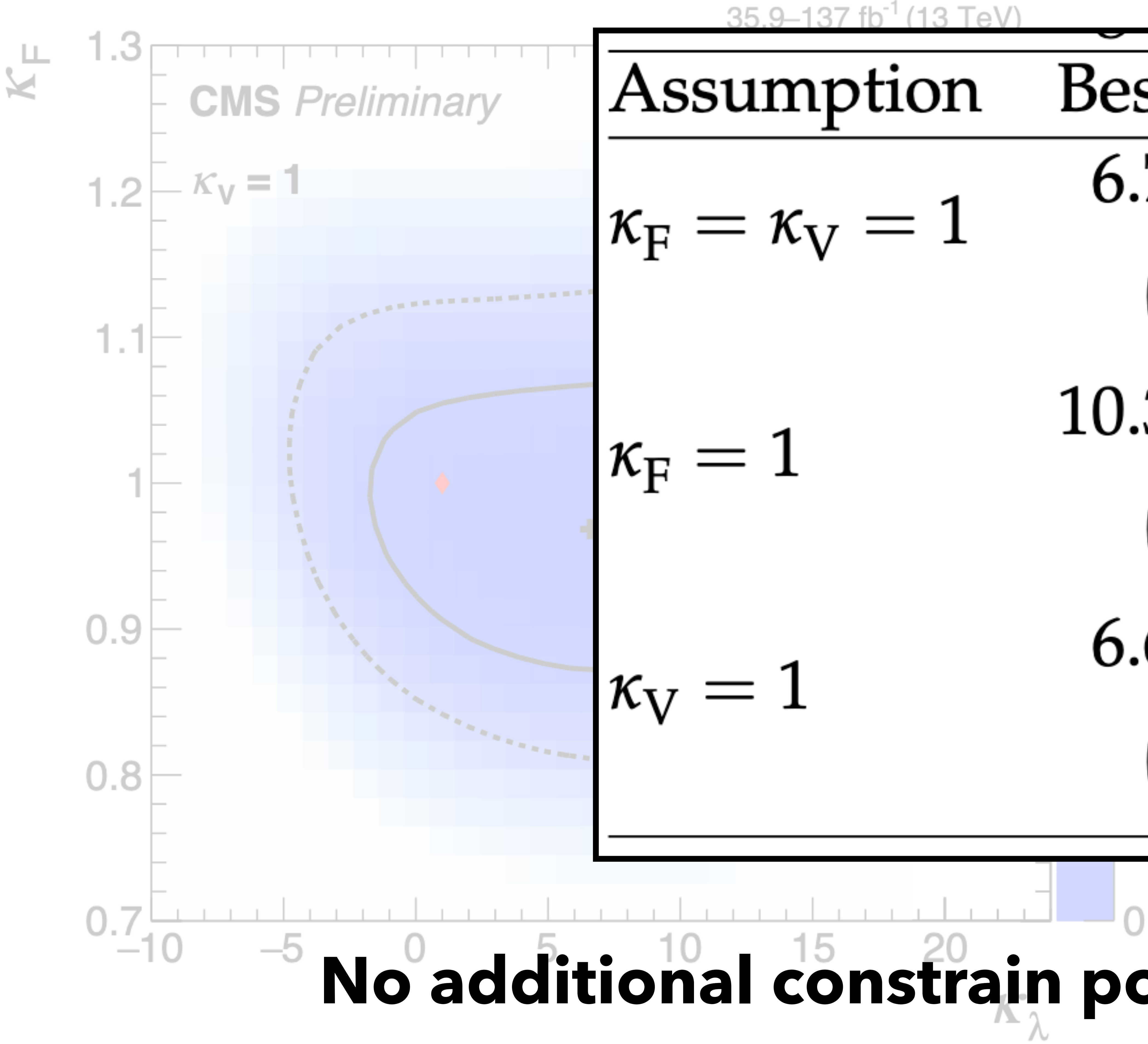
Constraint on $\kappa_\lambda = \lambda_{HHH}/\lambda_{\mathrm{SM}}$ from single-Higgs decay channels via modifications of the production cross sections and decay widths from NLO electroweak corrections



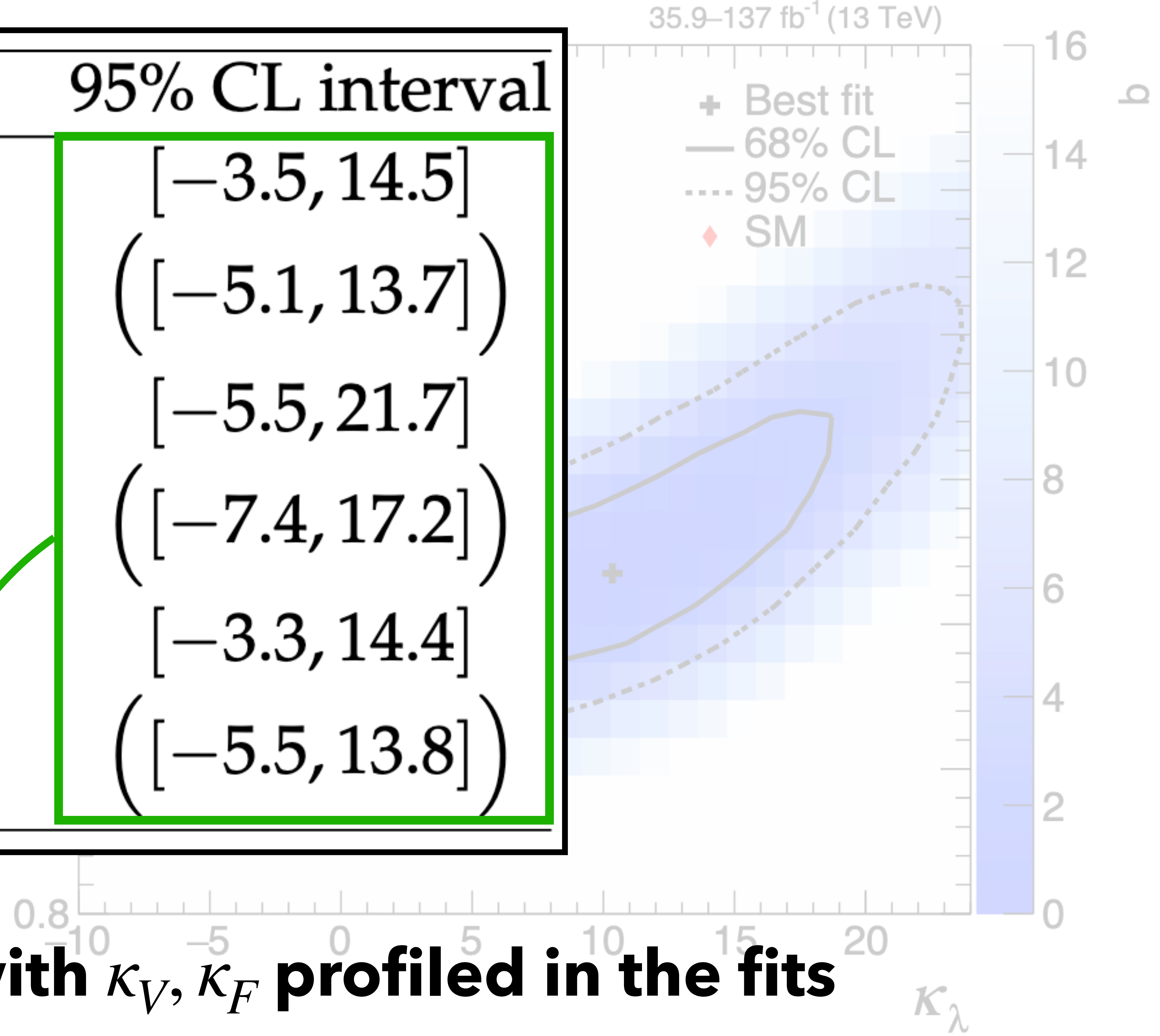


H boson self-coupling

Constraint on $\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$ from single-Higgs decay channels via modifications of the production cross sections and decay widths from NLO electroweak corrections



Assumption	Best fit κ_λ	95% CL interval
$\kappa_F = \kappa_V = 1$	$6.7^{+4.6}_{-6.6}$ $\left(^{+8.3}_{-3.8}\right)$	$[-3.5, 14.5]$ $([-5.1, 13.7])$
$\kappa_F = 1$	$10.3^{+6.1}_{-10.0}$ $\left(^{+8.8}_{-5.0}\right)$	$[-5.5, 21.7]$ $([-7.4, 17.2])$
$\kappa_V = 1$	$6.6^{+4.5}_{-6.1}$ $\left(^{+8.2}_{-4.0}\right)$	$[-3.3, 14.4]$ $([-5.5, 13.8])$

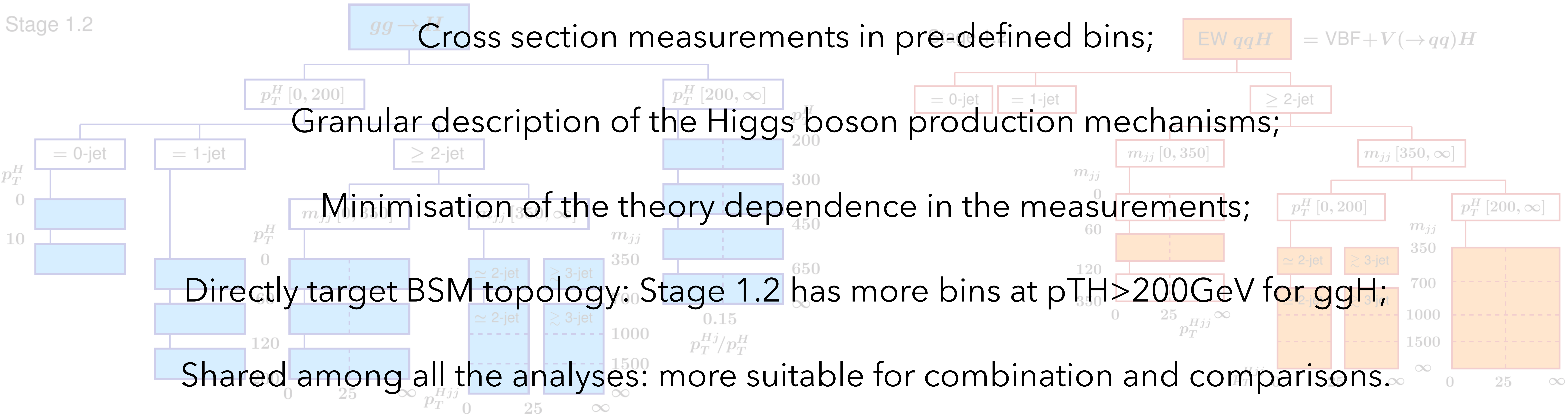


No additional constrain power with κ_V, κ_F profiled in the fits

Simplified Template Cross Section framework

The primary goal of **STXS** framework is to **minimise the measurement dependence on theory predictions without losing sensitivity**

Coverage of the entire phase space and **specific regions** designed **to detect BSM effects**



Cross section measurements in pre-defined bins;

Granular description of the Higgs boson production mechanisms;

Minimisation of the theory dependence in the measurements;

Directly target BSM topology: Stage 1.2 has more bins at pTH>200GeV for ggH;

Shared among all the analyses: more suitable for combination and comparisons.

EFT parametrization of STXS bins

STXS region (stage 0)	A_j
$gg \to H$	$8.73 \times 10^3\, c_G$
$qq \to Hqq$	$9.02\, c_{WW} + 0.6\, c_B - 0.797\, c_{HW} + 0.399\, c_A$
$qq \to H\ell\nu$	$42.5\, c_{WW} + 19.9\, c_{HW}$
$qq \to H\ell\ell$	$36.6\, c_{WW} + 10.5\, c_B + 15\, c_{HW} + 5.14\, c_A$
$gg/qq \to ttH$	$2.95\, c_u + 115\, c_G$

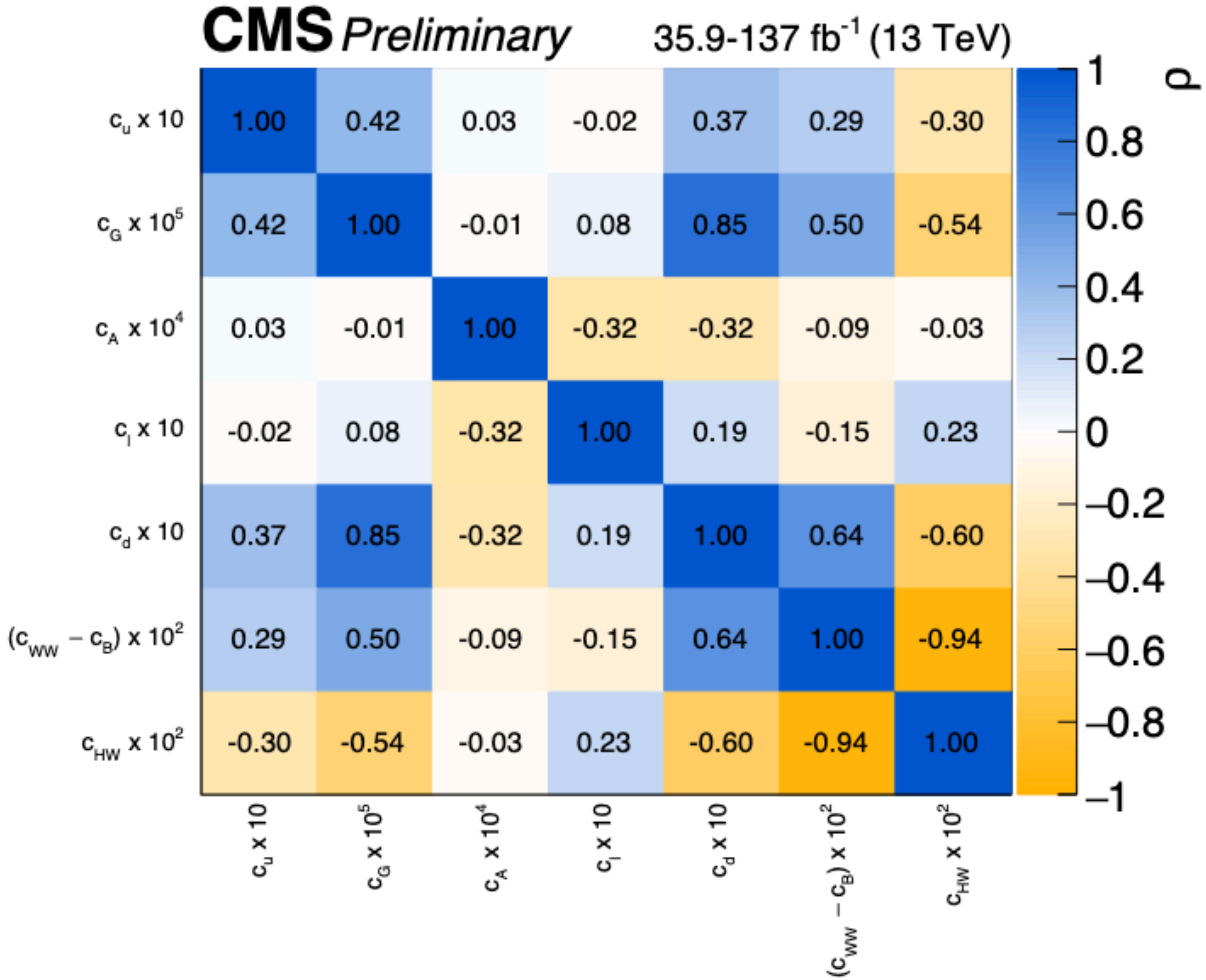
STXS region (stage 0)	B_{jk}
$gg \to H$	$1.95 \times 10^7\, {c_G}^2$
$qq \to Hqq$	$171\, {c_{WW}}^2 + 3.42\, {c_B}^2 + 114\, {c_{HW}}^2 + 0.874\, {c_A}^2 + 23.1\, c_{WW}\, c_B + 233\, c_{WW}\, c_{HW} + 6.22\, c_{WW}\, c_A + 15.3\, c_B\, c_{HW} + 2.02\, c_B\, c_A + 0.681\, c_{HW}\, c_A$
$qq \to H\ell\nu$	$912\, {c_{WW}}^2 + 558\, {c_{HW}}^2 + 1.3 \times 10^3\, c_{WW}\, c_{HW}$
$qq \to H\ell\ell$	$602\, {c_{WW}}^2 + 51.7\, {c_B}^2 + 321\, {c_{HW}}^2 + 10.7\, {c_A}^2 + 350\, c_{WW}\, c_B + 772\, c_{WW}\, c_{HW} + 102\, c_{WW}\, c_A + 227\, c_B\, c_{HW} + 31.4\, c_B\, c_A + 29.7\, c_{HW}\, c_A$
$gg/qq \to ttH$	$2.14\, {c_u}^2 + 6.13\, {c_{WW}}^2 + 1\, {c_B}^2 + 5.87\, {c_{HW}}^2 + 2.97 \times 10^4\, {c_G}^2 + 167\, c_u\, c_G - 0.31\, c_{WW}\, c_B + 11.9\, c_{WW}\, c_{HW} - 0.318\, c_B\, c_{HW}$

STXS Stage 1.0 and Stage 1.1 parametrizations in CMS-HIG-19-005

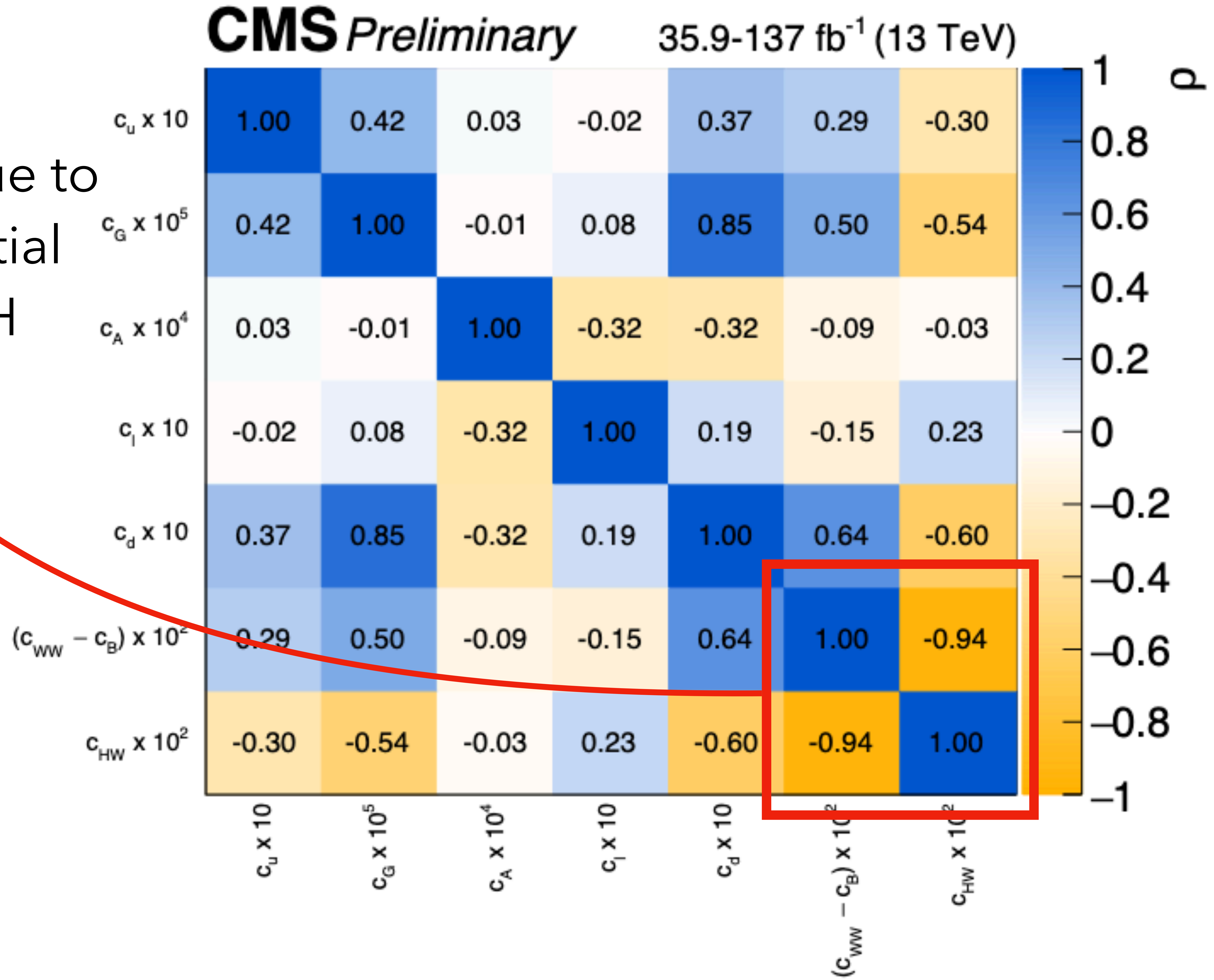
Limits on EFT parameters

HEL Parameters	Definition	Others profiled	Fix others to SM
$c_A \times 10^4$	$c_A = \frac{m_W^2}{g'^2}\frac{f_A}{\Lambda^2}$	$-1.03^{+1.53}_{-1.59}$ $\left(^{+1.59}_{-1.56}\right)$	$-0.78^{+1.11}_{-1.16}$ $\left(^{+1.10}_{-1.11}\right)$
$c_G \times 10^5$	$c_G = \frac{m_W^2}{g_s^2}\frac{f_G}{\Lambda^2}$	$1.43^{+3.20}_{-3.00}$ $\left(^{+3.13}_{-2.74}\right)$	$0.27^{+1.05}_{-1.05}$ $\left(^{+1.03}_{-1.01}\right)$
$c_u \times 10$	$c_u = -v^2\frac{f_u}{\Lambda^2}$	$0.68^{+0.82}_{-0.83}$ $\left(^{+0.83}_{-0.79}\right)$	$0.43^{+0.69}_{-0.69}$ $\left(^{+0.68}_{-0.67}\right)$
$c_d \times 10$	$c_d = -v^2\frac{f_d}{\Lambda^2}$	$0.59^{+1.03}_{-1.13}$ $\left(^{+1.08}_{-1.05}\right)$	$-0.01^{+0.31}_{-0.28}$ $\left(^{+0.30}_{-0.28}\right)$
$c_\ell \times 10$	$c_\ell = -v^2\frac{f_\ell}{\Lambda^2}$	$-0.57^{+0.74}_{-0.73}$ $\left(^{+0.72}_{-0.77}\right)$	$-0.75^{+0.60}_{-0.64}$ $\left(^{+0.58}_{-0.60}\right)$
$c_{HW} \times 10^2$	$c_{HW} = \frac{m_W^2}{2g}\frac{f_{HW}}{\Lambda^2}$	$-1.45^{+4.72}_{-3.03}$ $\left(^{+3.93}_{-3.27}\right)$	$0.77^{+0.84}_{-1.20}$ $\left(^{+1.04}_{-1.38}\right)$
$(c_{WW} - c_B) \times 10^2$	$c_{WW} = \frac{m_W^2}{g}\frac{f_{WW}}{\Lambda^2}, c_B = \frac{2m_W^2}{g'}\frac{f_B}{\Lambda^2}$	$2.16^{+2.84}_{-5.35}$ $\left(^{+3.46}_{-5.00}\right)$	$0.62^{+1.06}_{-1.22}$ $\left(^{+1.09}_{-1.23}\right)$

Correlations of EFT parameters

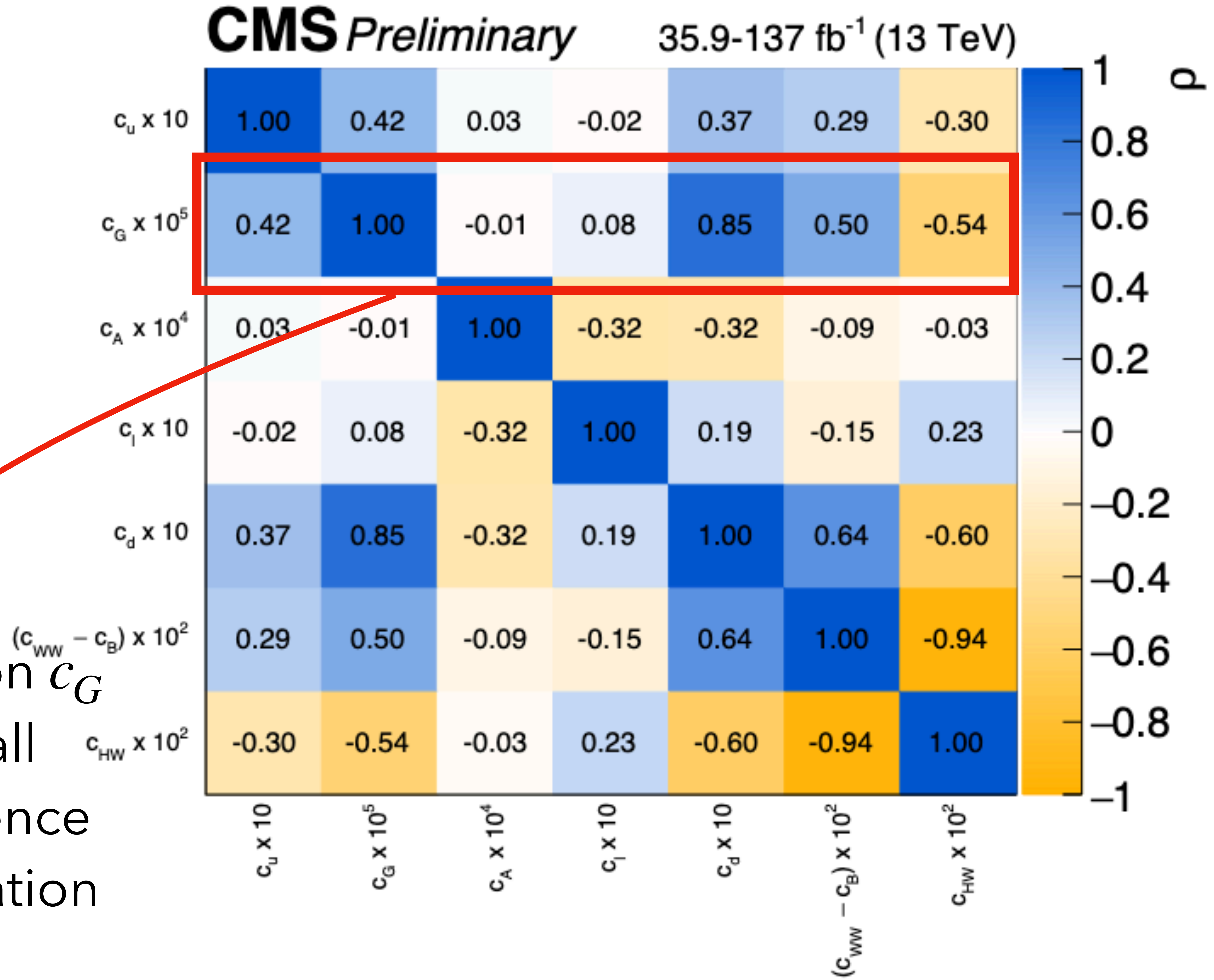


Correlations of EFT parameters



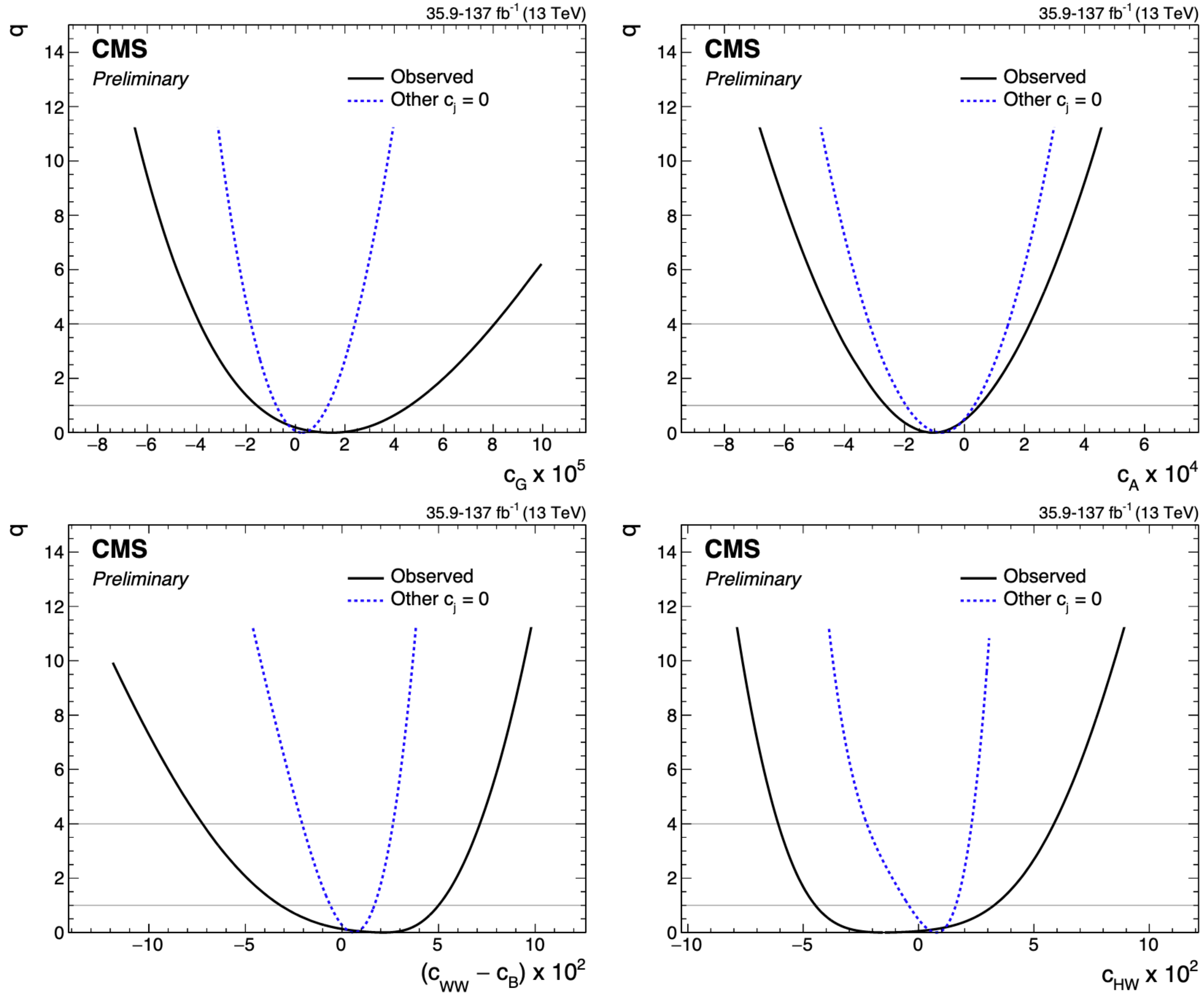
Large correlations due to the limited differential information for VH production

Correlations of EFT parameters

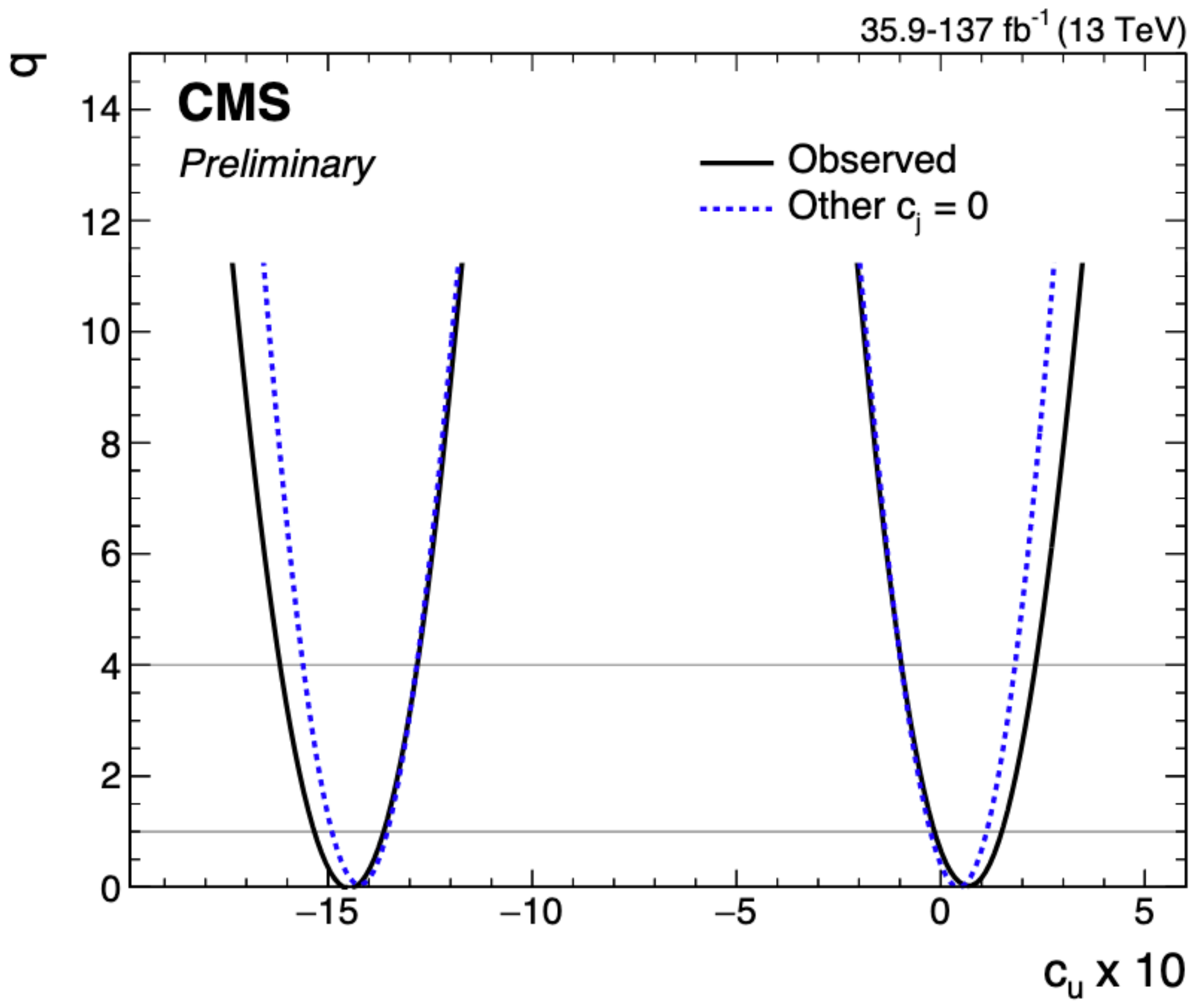


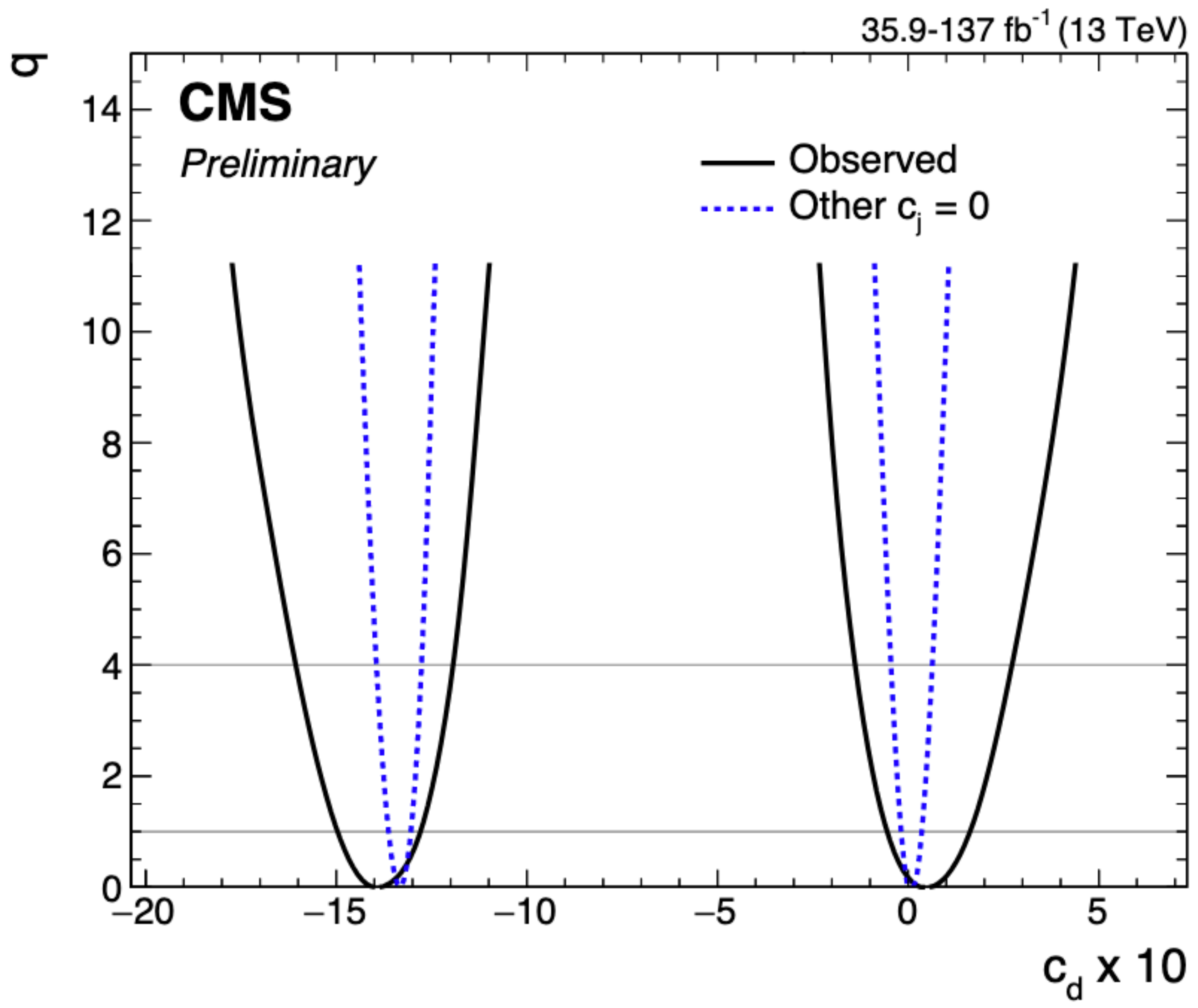
Large correlations on c_G coming from small kinematic dependence in STXS parametrization

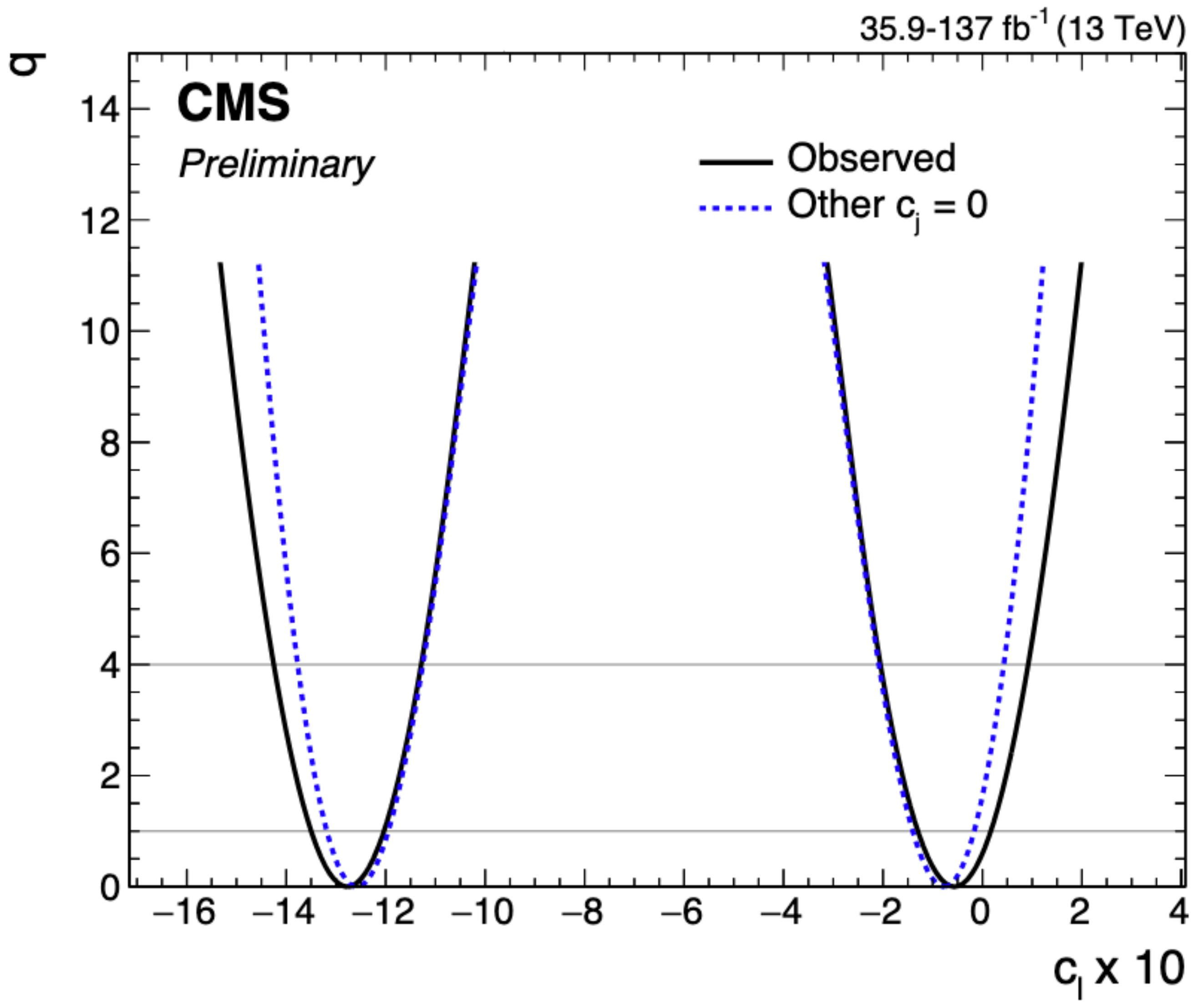
EFT parameters: likelihood scans



EFT parameters: likelihood scans

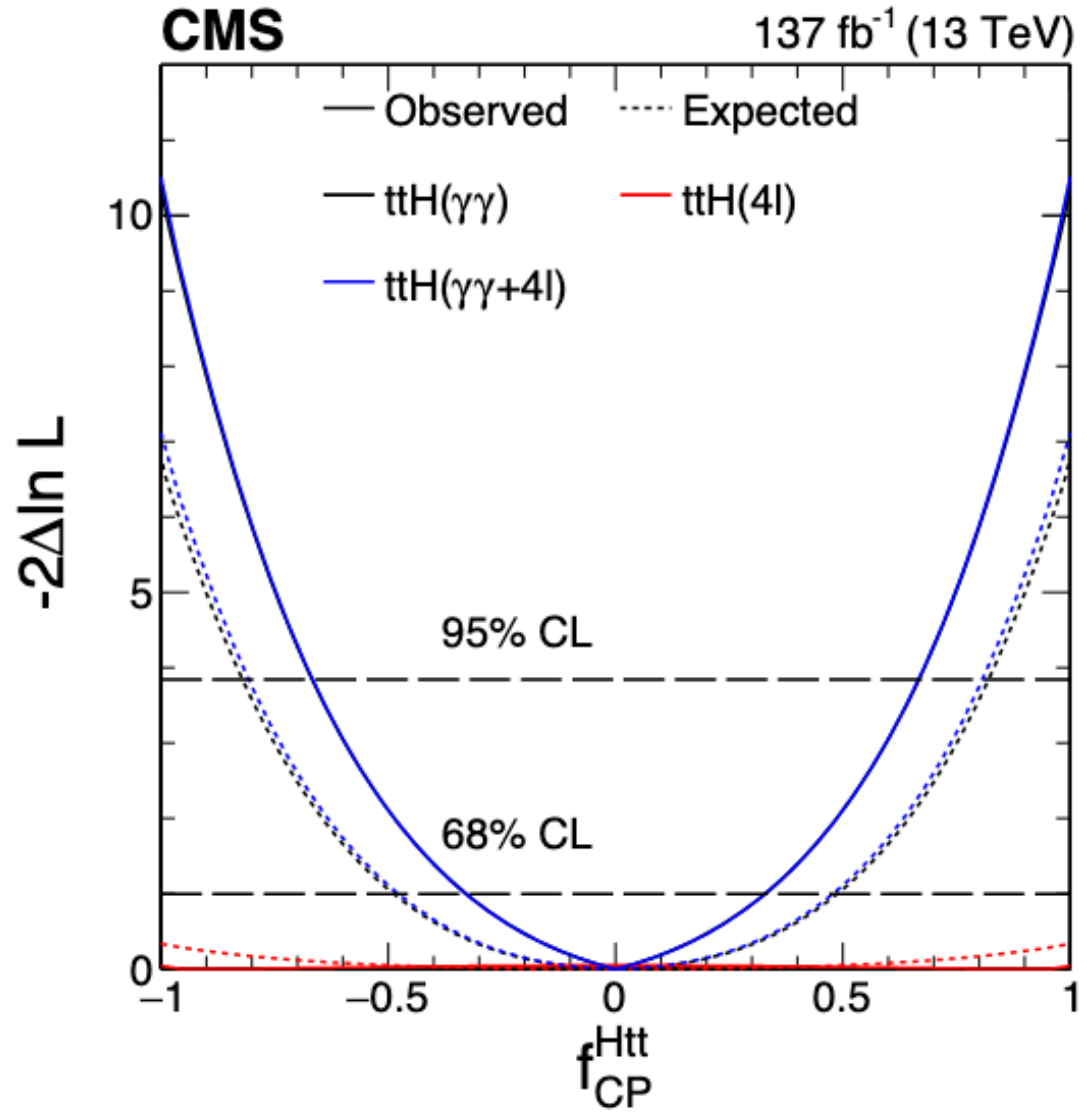


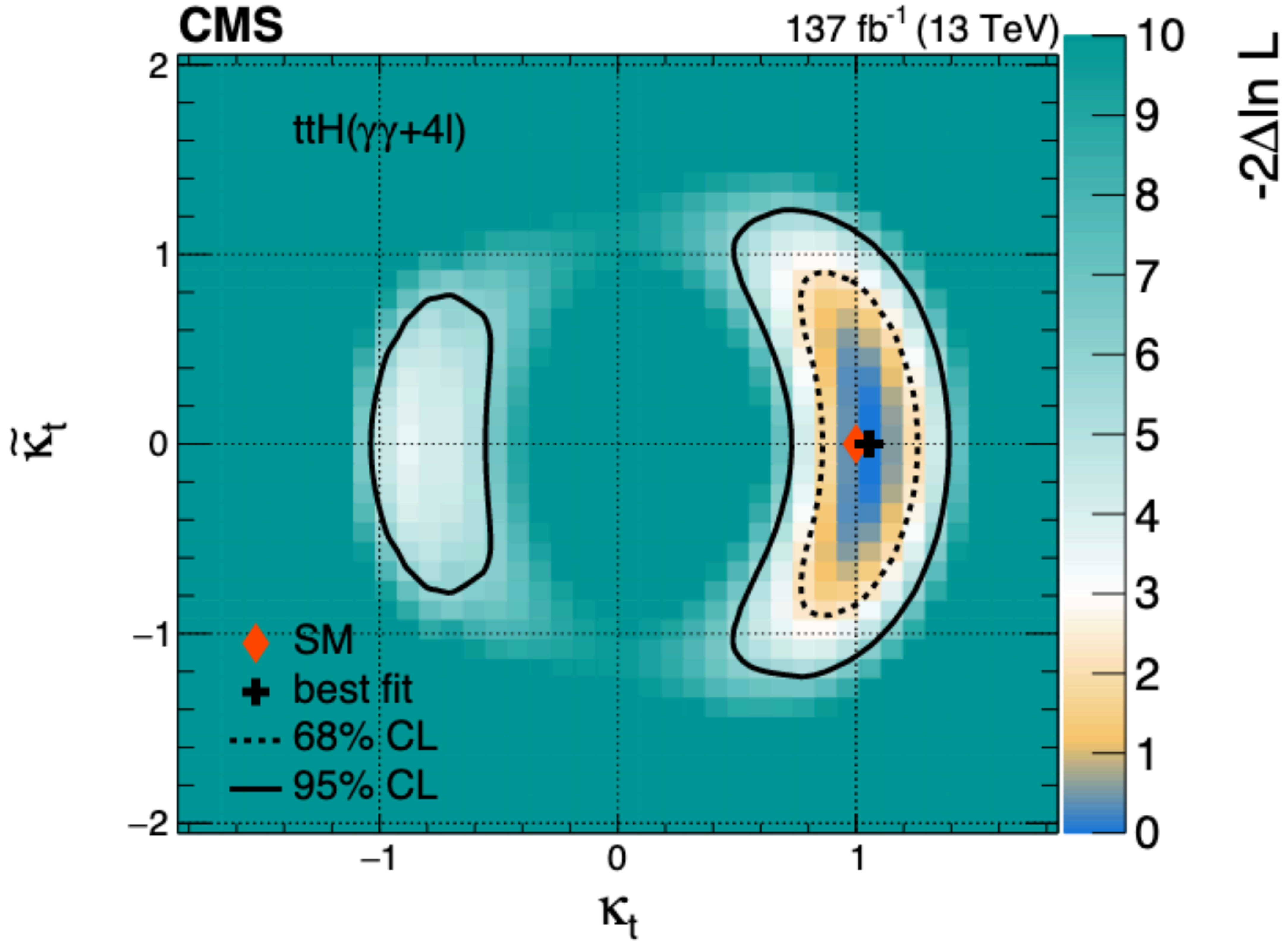




Htt couplings & EFT interpretation

$$f_{CP}^{\mathrm{Hff}} = \frac{|\tilde{\kappa}_f|^2}{|\kappa_f|^2 + |\tilde{\kappa}_f|^2}\,\mathrm{sign}\left(\frac{\tilde{\kappa}_f}{\kappa_f}\right)$$





Htt couplings & EFT interpretation